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VOLUME V

CRITICAL ASSEMBLIES

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CRITICAL ASSEMBLIES

Part II

Chapter 4

Written By:

L. D. P. King

CHAPTER 4

WATER BOILERS

L. D. P. King

4.1 WATER BOILER HISTORY

Estimates for the critical mass and dimensions of homogenous mixtures of both 49 and 25 in various moderating media were required early in 1943. This necessity arose from the production of appreciable amounts of active material in solution at separation plants. Early estimates of these quantities were made by several people.(1) (2)

(1) J. R. Oppenheimer and R. Serber, Unpublished.

(2) R. F. Christy and John A. Wheeler, CP-400.

In August 1943 it was decided to build the so called "water boiler" at site Y. The "water boiler" is a homogeneous chain reacting pile using an enriched uranyl solution in water. The purpose of this instrument was to gain experience in the operation and control of a chain reacting source and to prepare personnel and equipment for critical experiments as soon as kilograms of active material were available. The lack of large amounts of material necessitated the use of a slow neutron reaction, and the use of the best possible tamper or reflector.

A value of 10 kilowatts was arbitrarily chosen as a worth while operating level and preliminary plans and calculations made for such a power operation were completed September 1943.

It then appeared more advisable to first construct a boiler of much lower power. This would eliminate:

(1) the shielding requirements

(2) possible difficulties of keeping the uranium compounds in solution

(3) decontamination of the solution by separating out fission fragments

(4) uncertainty of gas evolution in appreciable quantities from fission fragments and decomposition of the water.

Plans for a low power boiler or lopo were completed in November 1943. A new building, Omega, in Los Alamos canyon was to house the water boiler. Its remote location eliminated any possible hazard to the rest of the technical area. Assembly of sphere and tamper were begun in March and the boiler went critical as soon as sufficient material was available, namely in May 1944 with 565 grams of U^{235}.

Due to the successful operation and experience gained from lopo it seemed desirable to construct a high power unit to be used as a strong neutron source for various experiments. A power of 1 kilowatt was chosen as a suitable value to give a flux of about 5×10^{10} with a minimum of cooling requirements. The original 10 kilowatt high power design was modified considerably. Essential design features were completed in October and concrete foundations and shield begun. Critical conditions were reached in December 1944 with 808 grams of U^{235}.

The operation of the boiler was completely successful until a precipitate formed and a drop in reactivity occurred on July 7, 1945 after 1100 kilowatt hours of operation. Some minor design changes were made along with maintaining the solution at a higher acid concentration, and the boiler was put in operation again. It has now (July 1946) run an additional 2600 kilowatt hours without further trouble.

4.2 LOW POWER BOILER (LOPO)[3]

(3) C. P. Baker, F. L. Bentzen, J. Bridge, R. E. Carter, H. Daghlian, H. Hammel J. Hinton, F. de Hoffman, M. G. Holloway, D. W. Kerst, L. D. P. King, H. M. Lehr, J. H. Midney, R. E. Schreiber, J. W. Starner, LA-134."Water Boiler"

4.2-1 Design Considerations

The primary purpose of the low power boiler was to obtain a chain reaction with a minimum of material as soon as enriched uranium became available.

The design features were therefore made accordingly: (1) A minimum of absorbing material. (2) The best possible tamper. (3) Accurate control of reactivity. (4) General simplicity consistent with safety.

(1) Corrosion tests[4][5] made by the chemists to determine the most suitable material for holding the active material showed that 18-8 stainless steel was the best available. Type 347 was especially good where welding was necessary. Welding in an inert atmosphere to prevent oxidation and pickling before use were found to be advantageous. The extremely low corrosion rate found permitted using a thin walled container.

Uranyl sulphate in water was chosen for the enriched solution since the sulphate is more soluble and has less neutron absorption than the nitrate.[6][7] The final solution composition is shown in

(4) G. Friedlander, P. H. Watkins, Water Boiler, LA 134 (Section on corrosion studies.)

(5) L. Helmholtz, J. Nevenzel, P. H. Watkins, Water Boiler Chemistry, Los Alamos Technical Series, Volume VIII, Chapter 7.

(6) L. Helmholtz, J. Nevenzel, P. H. Watkins, Water Boiler Chemistry, Los Alamos Technical Series, Volume VIII, Chapter 7.

(7) L. Helmholtz, G. Friedlander, Properties of Uranyl-Sulphate Solutions LAMS-30

Table 4.2-1A.

(2) Calculations[8] indicated that beryllium oxide would make the best neutron reflector or tamper. The metallurgy division, under the direction of Mr. Balke, developed a method of producing 3 x 3 x 6 inch bricks of density 2.7. These dimensions were chosen for convenience in constructing a pseudo sphere tamper 3 feet in diameter. The method used involves five steps:

(a) Pressing BeO powder for two hours in a steel die at 50,000 pounds per square inch;

(b) Sintering at 1250°C;

(c) Shaping by scraping, sawing, chipping, or grinding;

(d) Hot pressing in a graphite mold at 700°C and 2,000 pounds per square inch for two hours;

(e) Final shaping and finishing to tolerance by surface grinding. The special shaped bricks were made at Los Alamos while most of the rectangular bricks were made by the Fansteel Co., using the same method.

(3) In order to maintain criticality accurately it is necessary (a) to construct a control rod which could be adjusted to very close limits and (b) the temperature of the boiler had to be maintained accurately constant.

(a) The control rod consisted of a 34 inch long cylinder of cadmium formed by wrapping a thin strip around a brass tube 3/4 inch in diameter. Another brass tube is fitted snugly over the outside of the cadmium to eliminate any motion of the cadmium. The rod moved in a vertical direction with its end going from 12 inches

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(8) L. Helmholtz, J. Nevenzel, P. H. Watkins, Water Boiler Chemistry, Los Alamos Technical Series, Volume VIII, Chapter 7.

TABLE 4.2-1 A

Solution Composition

(A) Low Power Boiler $UO_2SO_4 \cdot 2\frac{1}{2}H_2O + H_2O$ = 15 liters

Element	Grams	Moles	σ_a Barns per atom	σ cubic centimeter	σ per gram U^{235}
U^{235}	580	2.47	640	955	1.6462
U^{228}	3378	14.19	12.1*	103	.1774
S	534	16.66	.45	4.74	.0082
O	14068	880.4	.0016	.85	1.832 total
H	1573	1561	.31	282.3	------
Stainless steel sphere and reentrant tube	1100	20	----	~ 36	

Density 1.348 cd 39°C

U^{235} concentration 14.67%

* From E. Fermi

TABLE 4.2-1 B

(B) Mock Solution for Boron Bubble Experiment 388gms/liter $U^*O_2SO_4 \cdot 2\frac{1}{2}H_2O$ + 10 gms/l H_3BO

Element	Grams per cubic centimeter	Barns per atom	σ Scatter	σ_a per cubic centimeter	σ_s per cubic centimeter
U^{235}	.000927	640	----	.000151	-----
U^{228}	.2247	12.1	8.2	.006818	.00466
B	.001749	721**	----	.070192	-----
S	.0303	.45	1.5	.000271	.00085
H	.1059	.31	41	.019001	2.59941
O	.9404	.0016	4.2	.000006	.14894

* Depleted

** Effective as compared with U^{235} for boiler neutrons

TABLE 4.2-1 C

(C) High Power Boiler $UO_2(NO_3)_2$ $6H_2O$ - H_2O - 13.65 liters

Element	Grams	Moles	σ_a Barns per atom	σ square centimeters	σ per gram U^{235}
U^{235}	869.6	3.7	640	1428	1.642
U^{228}	5341	22.44	12.1	163.5	0.188
N	731	52.2	1.75	55.1	0.063
O	13780	860	.0016	.8	0.00
H	1312	1302	.31	243	0.27
Stainless steel sphere and cooling coil	3000	55	---	~ 100	

Density - 1.615

U^{235} concentration 14.5%

below the sphere center to a somewhat higher position above the center. The motion of the rod was obtained by rotating a long steel screw (pitch .05 inches per thread) with a variable speed electric motor thru a clutch. A nut soldered to the inside brass tube has a key which prevents rotation of the rod itself. A ball bearing at the end reduces end play to 0.2 mil. The position of the rod is indicated by a Selsyn which is coupled by a 2:1 gear. This gives 0.100 inch per revolution of the Selsyn. The Selsyn on the control rack had a dial with 100 divisions each of which represented 1 mil vertical motion of the rod. Tests indicated that settings of the rod repeated to less than .5 mils. (See Figure 39).

(b) The reproduction factor K is very sensitive to the temperature θ of the solution. Calculations indicated that a change in reactivity of $10^{-3}/C^{\circ}$ was to be expected. At low power of a few milliwatts which would give adequate counting rates the temperature generation is negligible. However, fairly rapid fluctuations could be produced by external causes. A thermostated house was therefore built completely enclosing the boiler. The electronic control circuit[9] maintained the

(9) Developed by M. Sands, Unpublished.

temperature in the house to .01°C or K within 10^{-5}.

(4) From the estimates of the amount of material that would be required it seemed probable that a 1 foot diameter sphere would contain sufficient material and moderator without going to very high concentrations. (See Figures 1A and 1B). These curves are based on some unpublished calculations of Christy made in 1944.[10]

(10) R. F. Christy, Unpublished

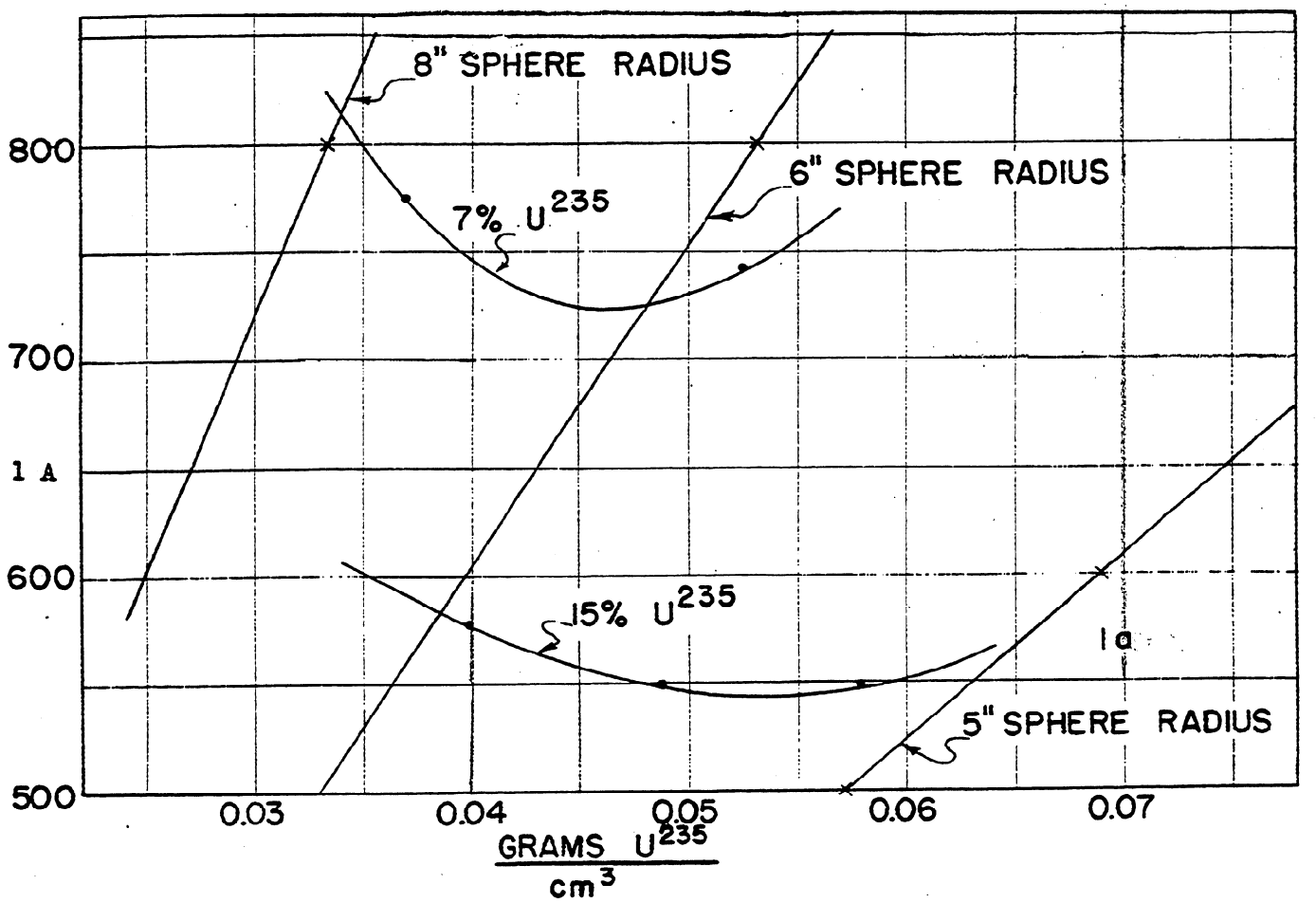


Figure 1 A

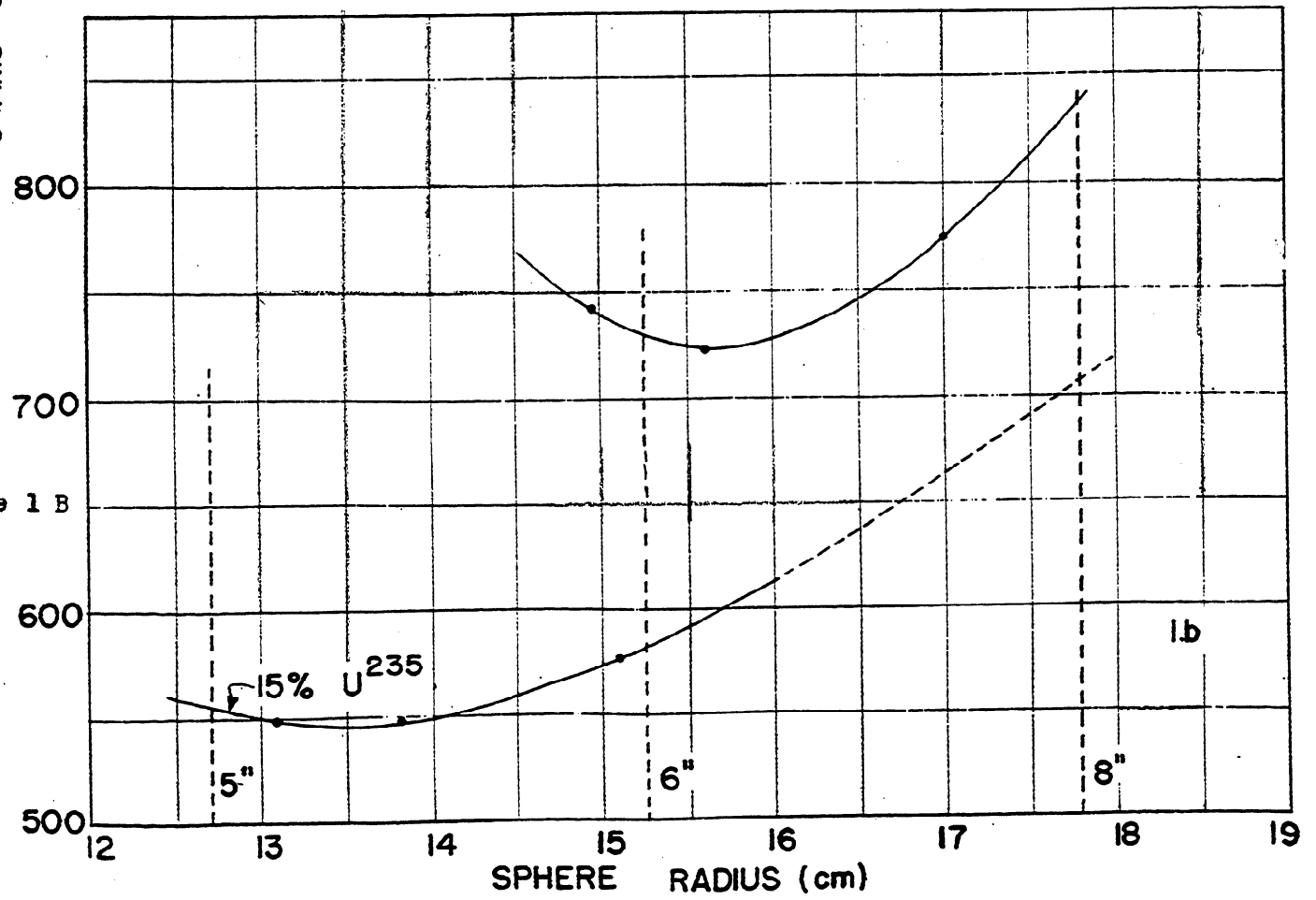


Figure 1 B

The constants used were σ_{U235} = 600 barns; ν = 2.15; τ (age) = 30 square centimeters.

It was therefore decided to use a 1/32 inch wall stainless steel sphere. The volume of the sphere was 14.96 liters. Due to lack of experience with chain reactions it seemed advisable not to leave the solution in a critical geometry at all times. For this reason the solution could be kept in a flat conical pan of poor geometry completely outside of the tamper when experiments were not in progress. This necessitated a pipe coming out of the lower hemisphere for raising and lowering the solution, a tube coming out of the upper hemisphere to insure complete filling of the sphere and a closed compressed air system to raise the solution from the lower pan. To prevent water vapor from leaving the solution and thereby changing the concentration, thick walled rubber balloons contained in a pressure tank supplied the inlet air, light rubber balloons took up the air displaced by the solution as it filled the sphere. Electrical contacts served to indicate the height of the solution in the upper tube. A monometer was used to observe the rate of rise of the solution into the sphere and detect any air leaks in the closed system. (See Figures 2 and 3).

(5) Numerous safety features were included in the design to prevent accidental loss of solution or unexpectedly reaching supercritical conditions (see Figure 4).

The safety rod was automatically dropped if the neutron level rose too high or the power failed. The active material was dumped into the lower pan if:

(a) The solution rose too high in the upper pipe

(b) A leak developed anywhere in the sphere (by shorting nylon covered wires wrapped around the sphere).

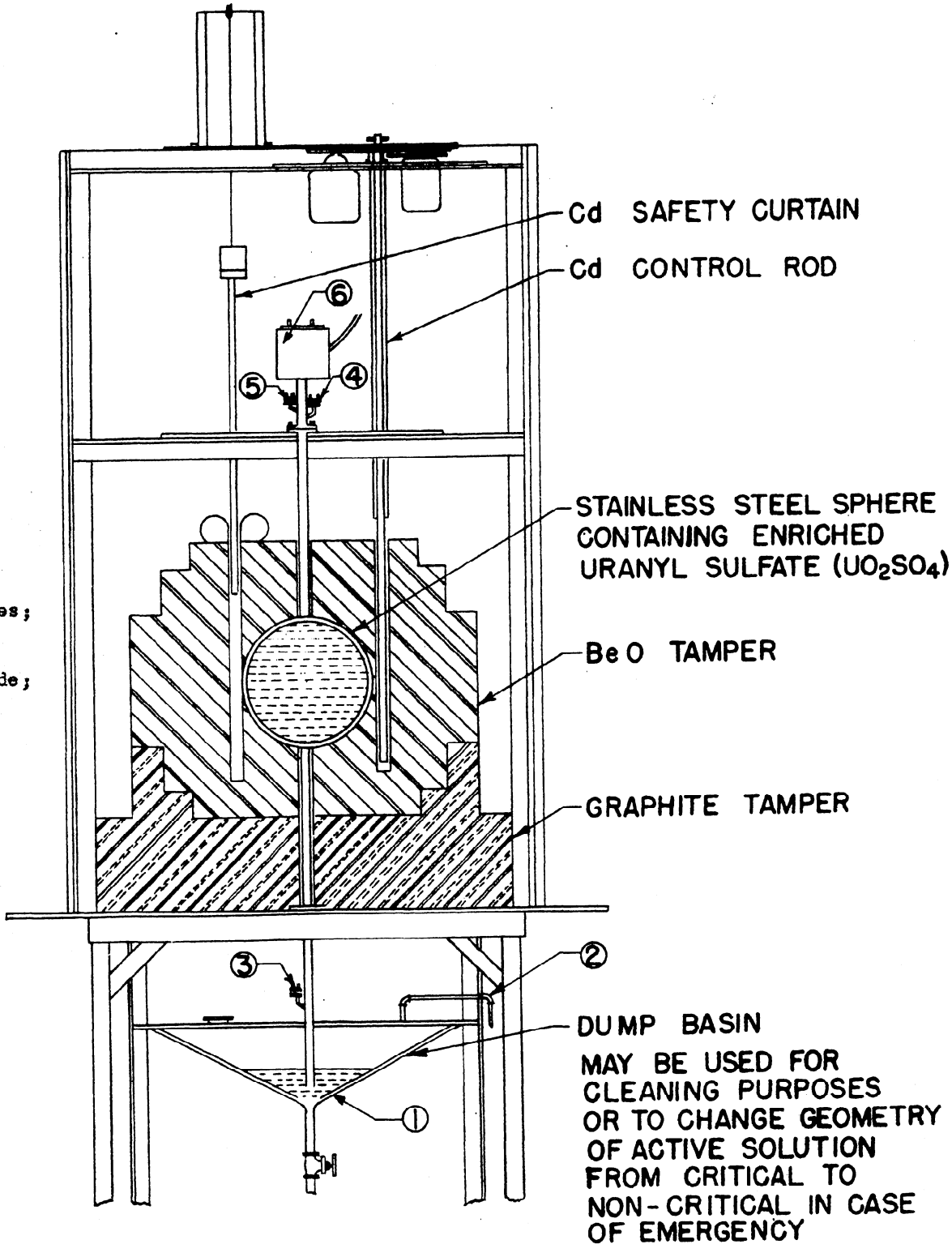


Figure 2

(1) Conical pan;

(2) Air pipe;

(3), (4) Level electrodes;

(5) Safety electrode;

(6) Overflow.

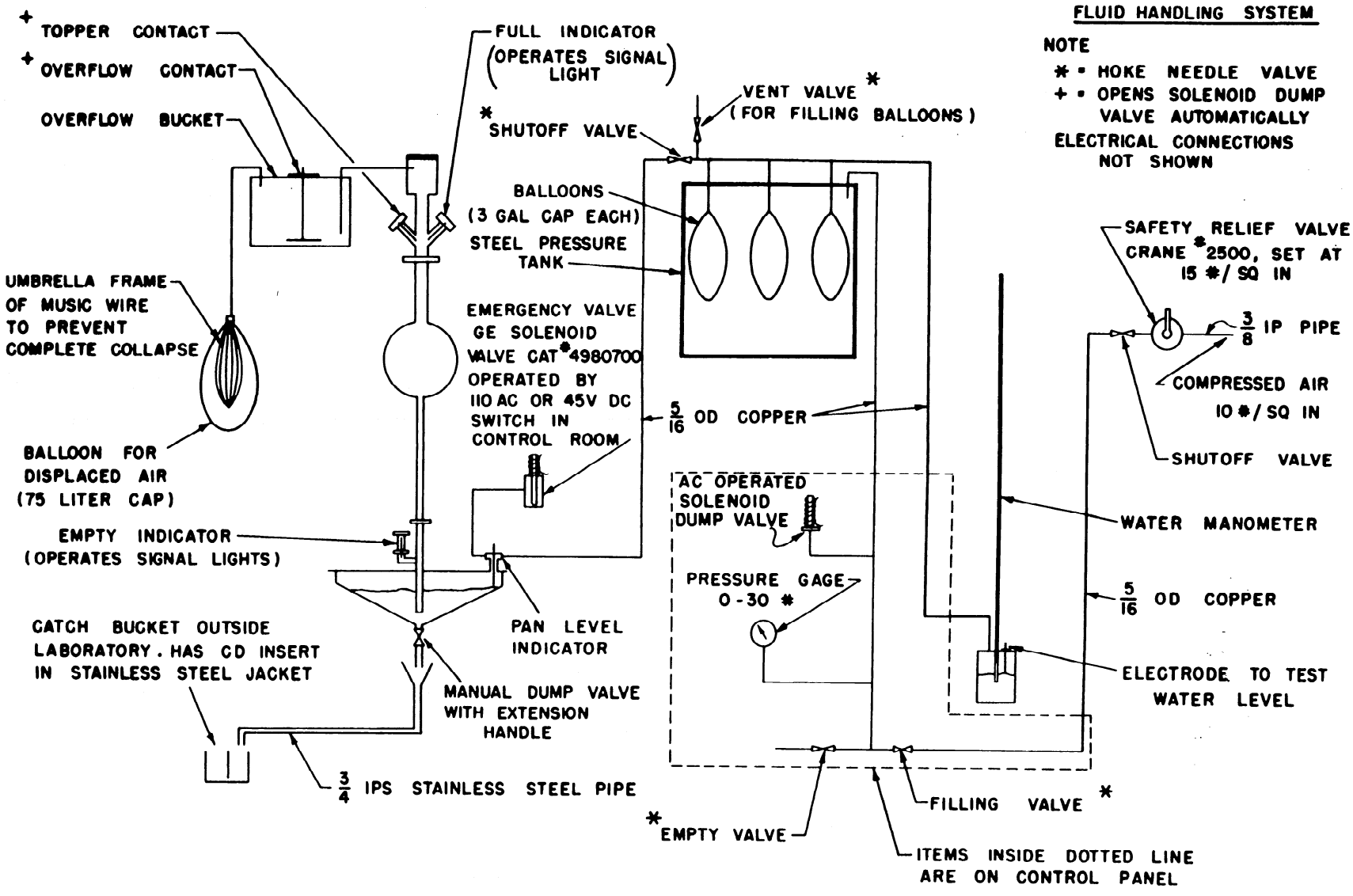


Figure 3

Fluid Handling system.

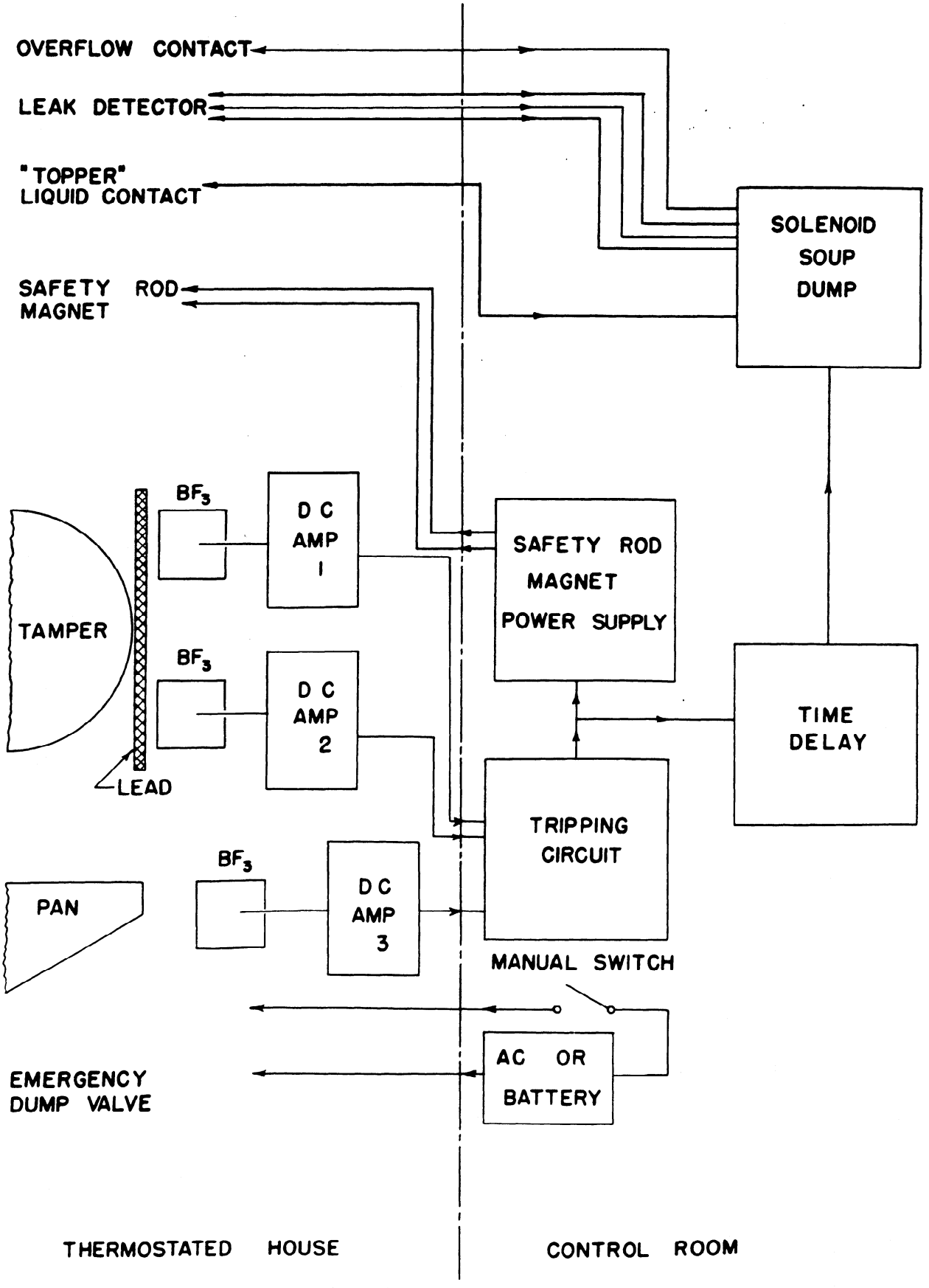


Figure 4

Safety Circuits.

Arrows in lines indicate direction

of controlling impulses.

(c) If after a short time the neutron level continued to rise above a predetermined level (the delay permits the safety rod to operate first).

A safety catcher pan was placed underneath the tamper and sphere to prevent the loss of material due to leak or overflow. All safety devices operated in case of power failure. As a final precaution the conical pan was provided with a remote manually controlled dump valve which drained the solution through an underground pipe into a stainless steel bucket with cadmium inserts to discourage any further chain reaction. This provided a possible way of removing the solution from the building which seemed advisable in the case the solution became too radioactive.

4.2-2 Approach to Critical

Since this was the first chain reaction with an enriched material, considerable precautions were taken before approaching critical.

The general procedure was as follows. Five independent detectors placed in different positions were used to determine the multiplication of a 200 mc Ra Be source placed at the center of the sphere by means of a thimble type reentrant tube thru the upper pipe. A zero reading, i. e. for no multiplication, was obtained by filling the sphere with distilled water. The empty sphere and source were used to standardize all detectors before and after each change of concentration.

The chemists then proceeded to add uranyl sulphate by removing one or two liters of the solution in the conical pan and dissolving an additional amount of material. An electric stirrer was run for 15 minutes to make sure of adequate mixing before the solution was run up into the sphere. Further mixing was obtained by raising and lowering the solution between pan and sphere until

no further change in counting was detectable. This usually required three to five fillings of the sphere. The first 11 additions contained about 40 grams each of U^{235}, the next 4 about 20 grams each of U^{235} and the last 3 about 5 grams U^{235} each.

The detectors used to determine the multiplication were (1) Indium foils with and without cadmium in the tamper three inches from the sphere surface; (2) Manganese foils in the reentrant tube placed at the center and near the edge of the sphere; (3) An external BF_3 chamber bare and in a paraffin block 9 inches x 113 inches covered with cadmium; (4) A small U^{235} chamber about 5/16 inches O. D. placed in a reentrant tube about 3 inches from the center; (5) A large U^{238} chamber placed against the sphere in the north part of the tamper (this chamber had 248 square centimeters area covered with 2 grams of U^{238}).

Table 4.2-2 shows the results obtained with these detectors. The shape which the curves of Figure 5 have when plotting reciprocal count against mass can be qualitatively understood fairly easily. Thermal detectors placed inside the reacting region should give an approximate straight line and hence the best extrapolated estimate of the critical mass, intercepting the abscissa at the critical mass, (detectors placed at the center were too near the 200 mc Ra Be source and hence gave a concave downward curve). The best position for such a detector is probably at the node of the third harmonic of the thermal neutron distribution which has a high peak at the source. One of the manganese detectors was placed approximately in this position after the strong source effect was observed at the central position. Detectors placed outside the reactor should ideally give curves concave upward since they count both fast and slow leakage. It is apparent from the trend of all the curves that rather accurate predictions of the critical mass could be made before actually going critical. When the

TABLE 4.2-2

Mass (gms) "25" In Sphere	Foils In + Cd 1/c	Foils In 1/c	Foils Mn* 1/c	Foils Mn** 1/c	BF_3 Baro 1/c	BF_3+Cd+CH_2 1/c	BF +CD 1/c	"25" 1/c	"28" 1/c	
0 (dist.H_2O)	1	1	1	1	1	1	1	1	1	0
46.8	.783	.783	-	.973	.835	.857	-	.909	.889	1
140.1	.495	.524	-	.900	.560	.650	.626	.752	.589	2
183.4	-	-	-	-	.465	-	-	.693	-	3
225.7	.303	.359	-	.820	.379	.449	.440	.625	.395	4
266.5	-	-	-	-	.316	-	-	.580	-	5
303.3	.195	.241	-	.774	.257	.307	.295	.483	.284	6
343.0	-	-	-	-	.208	-	-	.411	-	7
380.2	.118	.151	.318	.534	.164	.198	.196	.359	.178	8
435.3	-	-	.230	-	.109	-	-	.267	-	9
474.9	.052	.072	.175	.290	.070	.092	.088	.191	.081	10
501.35	-	-	-	-	.055	-	-	.145	.065	11
518.47	.029	.038	.101	.195	.042	.052	.050	.117	.046	12
540.10	-	-	.063	.128	.026	-	-	.073	.027	13
555.17	-	-	-	-	-	.016	-	-	-	14
564.10	-	-	-	-	-	.008	-	-	-	15
570.879	-	-	-	-	-	.0025	-	-	.0022	16
574.829	Critical with Control Rod at 16.5" Above its Bottom Position									17

(572.8 gm) Critical mass with rod out
(565.5 gm) " " " " " , reentrant tube and 28 chamber removed
* Mn foils which were put approximately at node of third harmonic
** Mn foils in center of sphere

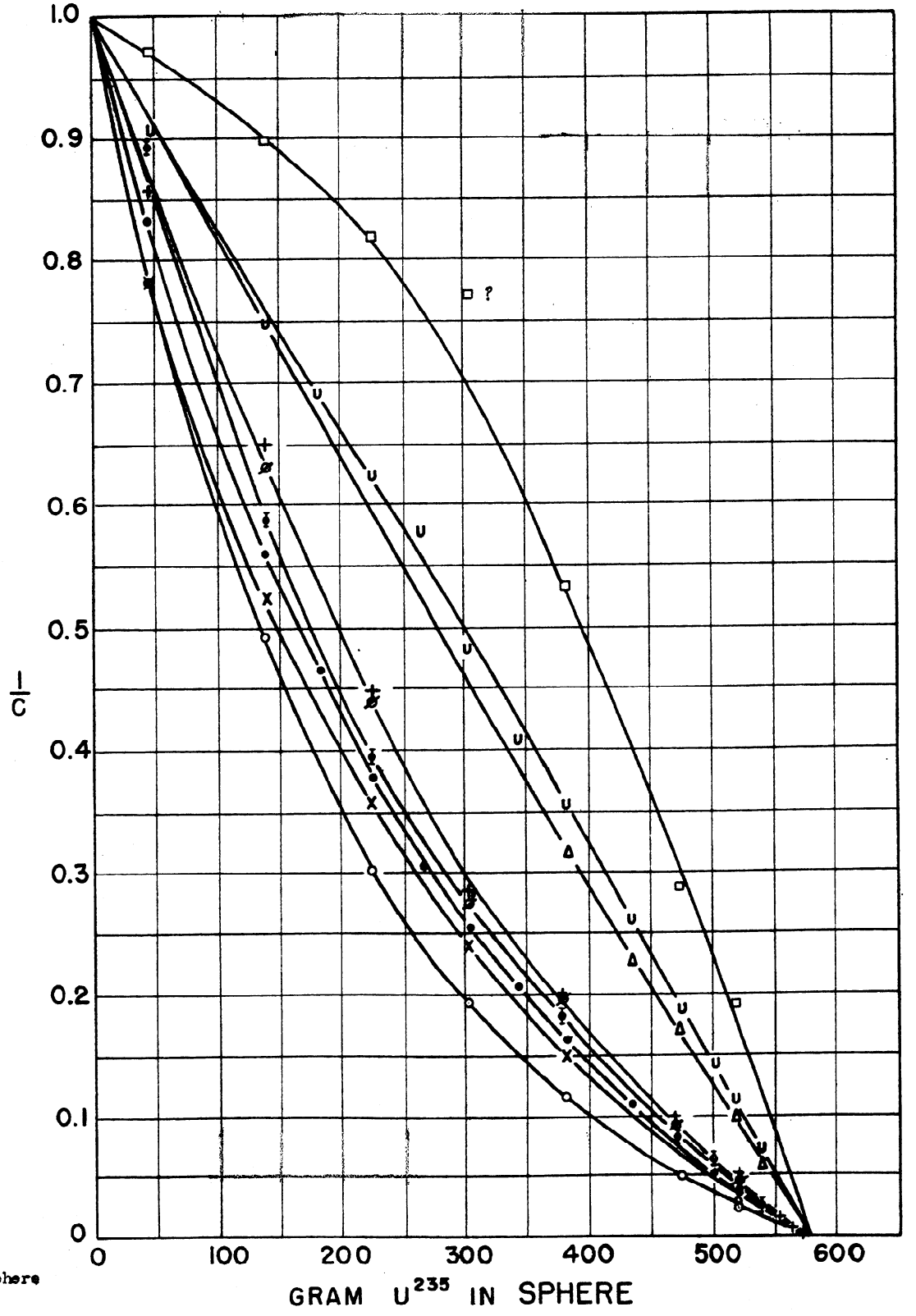


Figure 5

○ - In + Cd Foils 3" from Sphere

X - In Foils 3" from Sphere

△ - Mn Foils at Node 3rd Harmonic

□ - Mn Foils at Center of Sphere

• - BF_3 Bare Outside Tamper

+ - BF_3 + Cd + CH_2 Outside Tamper

ø - BF_3 + Cd Outside Tamper

U - U^{235} Chamber 3" from Center

I - U^{238} Chamber Against Outside of Sphere

last addition had been made, the control rod was pulled out slowly until a good counting rate was obtained, the driving source removed and the boiler ran itself, the neutron level responding to the control rod.

The U^{235} in the sphere at this time was 574.8 grams. Correcting for the rod position, a missing tamper block due to the presence of one of the recording chambers, and a small reentrant tube gave 565.5 grams of U^{235} as the critical mass. This checked original calculations(11) extremely well, probably somewhat fortuitously.

(11) R. F. Christy, Unpublished.

The highest power at which Lopo was run was about 50 millwatts.

4.2-3 Experiments with Lopo

(1) Control rod calibration(12)

(12) C.P. Baker, F.L. Bentzen, J. Bridge, R.E. Carter, H. Daghlian, H. Hammel, J. Hinton, F. de Hoffman, M.G. Holloway, D.W. Kerst, L.D.P. King, H.M. Lehr, J.H. Midway, R.E. Schreiber, J.W. Starner, "Water Boiler", LA-134.

When the critical conditions were initially reached, the control rod was part way in. Active material was then removed from the sphere by dilution until the control rod was just out with the boiler still critical. Eight small additions of approximately 2 grams each of material were then made and in each case the rod position for criticality determined. Figure 6 shows the curve of the equivalent mass of U^{235} as a function of control rod position. The control rod is all the way in at zero inches. In all measurements the solution is raised to the same position in the upper pipe, about 90 centimeters above sphere level. This was approximately to the top of the tamper. Criticality was found to be insensitive to the solution level in this upper tube except for the first few centimeters. If the level above the sphere is measured in centimeters, and the total effect expressed

Figure 6

in grams of U^{235} equivalent, the measured values are 1 gram at 2.5 centimeters, 2 grams at 7 centimeters, 3 grams at 19 centimeters, 4.5 grams at 90 centimeters.

(2) Temperature effect.(13)

(13) C. P. Baker, F. L. Bentzen, J. Bridge, R. E. Carter, H. Daghlian, H. Hammel, J. Hinton, F. de Hoffman, M. G. Holloway, D. W. Kerst, L. D. P. King, H.M. Lehr, J. H. Midway, R. E. Schreiber, J. W. Starner, Water Boiler LA-134.

Due to the large expansion coefficient of the water solution the neutron leakage is strongly dependent on temperatures since both neutron age and thermal diffusion length vary with temperature. This produced quite a change in the critical position of the control rod. The effect is measured by accurately determining the critical rod positions for various temperatures of the solution. The average value found was .75 grams per degree C at 39 degree C. This is partly due to the loss of solution from the sphere due to the thermal expansion. Correcting for expansion gives .55 grams per degree C.

(3) Absolute calibration of the water boiler in terms of K(14)(15)

(14) F. L. Bentzen, J. Bridge, F. de Hoffman, D. W. Kerst, L. D. P. King, G. Friedlander: Criticality of the Water Boiler and Dispersion of the Neutron Emission per Fission, LA-183.

(15) F. de Hoffman, L. D. P. King, G. A. Young: Criticality of the Water Boiler and Dispersion of the Neutron Emission per Fission, LA-183 A.

In order to determine the relation between grams and the actual reproduction factor K of the boiler a so called "boron bubble" experiment was performed. The equivalence of K and grams of U235 was obtained by observing the critical control rod setting under normal conditions and then the setting after the introduction of a small volume or bubble (15.17 cubic centimeters) containing a

mock solution. The mock solution consisted of an appropriate mixture U^{238} and H_3BO_3 in water. The absorption and scattering cross-section of the mock solution matched that of the boiler solution closely, see Tables 4.2-1A and 4.2-1B, (except of course, that no fissions occurred in the mock solution). No change in criticality could be detected by the insertion or radial motion of the small volume when filled with the boiler solution. The bubble consisted of a thin walled lucite sphere supported on a lucite rod. The experimental results when the bubble with the mock solution is moved radially, is shown in Figure 7. The conversion from control rod setting to grams is read from Figure 6. If ΔM is the effective grams of U^{235} for any radial position then

$$\overline{\Delta M} = \frac{\int_o^r 4\pi r^2 \Delta M dr}{\int_o^r 4\pi r^2 dr}$$

is the equivalent of distributing the mock solution in the bubble uniformly throughout the sphere. The final value for ΔM was 1.843 grams of U235. A 7.5 per cent correction for slight differences in absorption between the mock solution and the actual solution was applied to get this result. For the mock solution

$$\sigma_{s/cc} = 2.749 \text{ cm}^2 \quad \text{and} \quad \sigma_{a/cc} = .0965 \text{ cm}^2$$

for the normal solution

$$\sigma_{s/cc} = 2.734 \text{ cm}^2 \quad \text{and} \quad \sigma_{a/cc} = .0897 \text{ cm}^2$$

Thermal cross sections were used throughout, except for boron. For this case and effective cross section of boron compared to that of U^{235} was determined assuming the higher energy spectrum to be that of pure hydrogen. This assumption is reasonable due

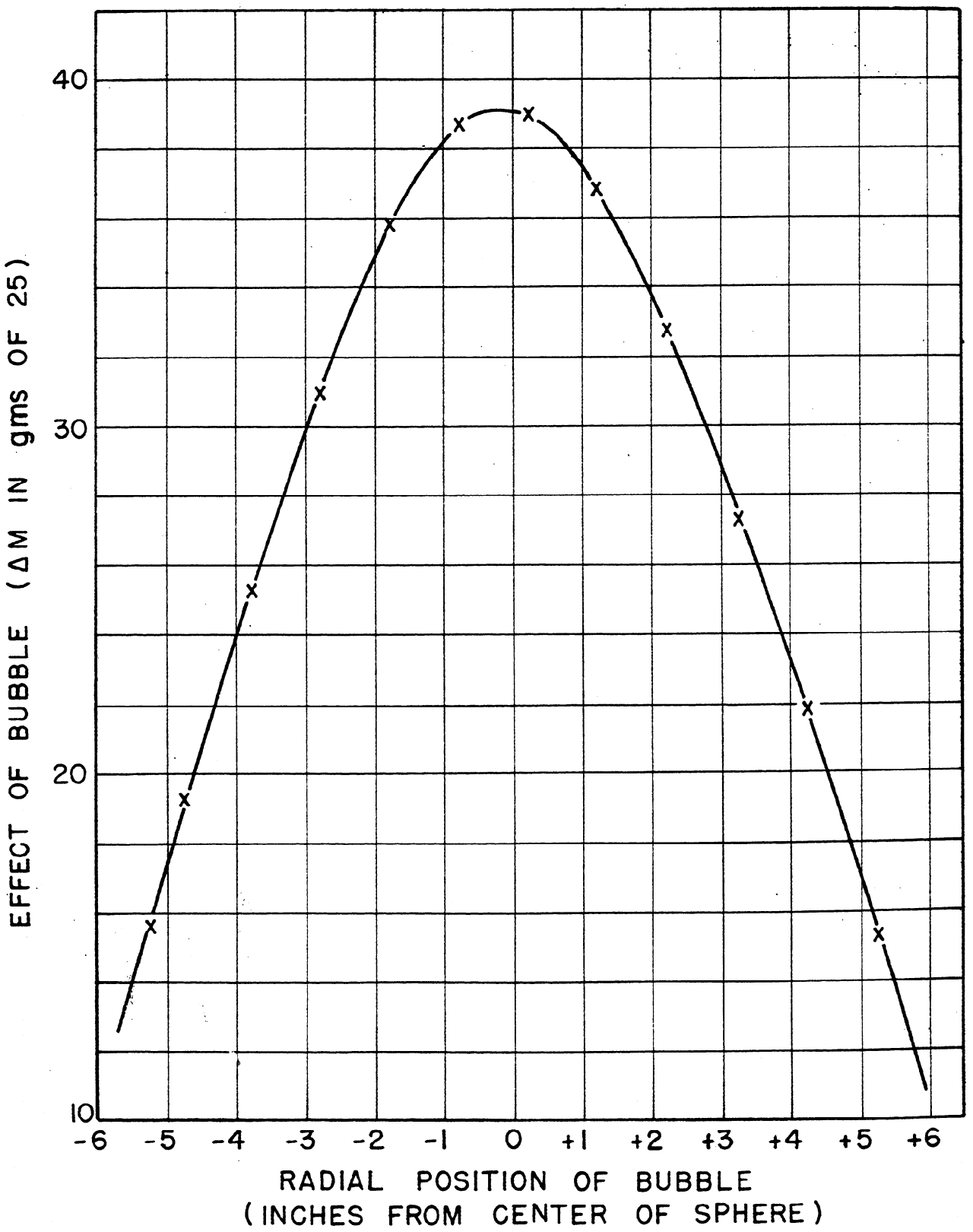


Figure 7

A Boron-bubble experiment.

△M vs Radial Position

to the large hydrogen content in the boiler solution. The effective boron cross section was found to be 2.5 per cent higher than the thermal value.

If ΔM were distributed uniformly throughout the sphere ΔK would be very nearly proportional to ΔM. Since the actual localized volume ΔM used was quite small, it is reasonable to assume that this proportionality is true.

$$\text{Then } \frac{K\ (\text{mock})}{K\ (\text{original } (=1))} = \frac{V - \Delta V}{V} = 1 - \frac{\Delta V}{V}$$

$$\text{and } \Delta K = 1 - K = \frac{\Delta V}{V} = \frac{V \text{ bubble}}{V \text{ sphere}} = \frac{15.17}{15 \times 10^3} = 1.01 \times 10^{-3}$$

Since $\overline{\Delta M} = 1.843$ grams of U^{235} and $\Delta K = 1.01 \times 10^{-3}$ for this $\overline{\Delta M}$ one obtains as the equivalence between reactivity and grams of U^{235}

$5.48 \times 10^{-4}\ \Delta K/gm$ or $548\ \mu Re/gm$ (a microres = $K \times 10^6$)

This value checks, no doubt fortuitously, within a percent the theoretical value[16] made prior to the above result. (An error in the original determination[17] has been corrected in[18] after the calculation[19] was made.)

(16) F. de Hoffman, L. D. P. King, G. A. Young: Criticality of the Water Boiler and Dispersion of the Neutron Emission per Fission, LA-183 A.

(17) F. L. Bentzen, J. Bridge, F. de Hoffman, D. W. Kerst, L. D.P. King, G. Friedlander: Criticality of the Water Boiler and Dispersion of the Neutron Emission per Fission, LA-183.

(18) F. de Hoffman, L. D. P. King, G. A. Young: Criticality of the Water Boiler and Dispersion of the Neutron Emission per Fission, LA-183 A.

(19) E. Fermi, J. Hinton: Dependence of Reactivity of Water Boiler in the Mass of U^{235} in the Sphere, LA-470.

The calculations were made by determining the negative source (using the diffusion equations for sphere and tamper) necessary to keep the boiler running at a constant value when x grams of U^{235} are added. The fission distribution was assumed the same as the experimentally measured thermal neutron distribution. The effectiveness of a fission source at different points in the sphere was approximated by using a Ra Be source curve.
The equivalence of grams of U^{235} and reactivity can be estimated quite well from the cross sections of the solution components and any absorbing materials such as the stainless steel sphere or control rod. From Table 4.2-1 A

$$\bar{\nu} \text{ of } 14.67\% \text{ Uranyl sulphate solution} = \frac{2.1 \times 954.9}{954.9 \times 102.9 + 4.74} = 1.8873$$

$$K^{\infty} = \frac{\sigma_a(U^{235}) \times \bar{\nu}(U^{235}) \times Mc(U^{235})}{\sigma(U^{235} + H_2O + \text{Steel})} = \frac{1.832 \times 572 \times 1.8873}{1.832 \times 572 + (282 + 36+6)} = 1.4416$$

where 572 is critical mass (U^{235} in sphere)

$$L = \text{leakage} = \frac{1}{1.4416}$$

$$K = \frac{M(U^{235}) \times \sigma/gm U^{235} \times L}{M(U^{235}) \times \sigma/gm(U^{235}) + (\sigma H_2O + \sigma \text{ steel} + \sigma \text{ reentrant tube})} = \frac{M \times 2.39842}{1.832 \times M + 324}$$

and

$$\Delta K = 406 \alpha R/gm\ U^{235}$$

For the boron bubble experiment the reentrant tube was out (6.2 grams U^{235} equivalent) and the control rod set at 7.15 inches (9 grams U^{235} equivalent). The estimated absorption for the rod is 195 square centimeters, (the effective surface area of the cadmium cylinder is used to get this value), that for the reentrant tube 6 square centimeters, or total square centimeters

equal 318 + 195-6 = 507

Term $K = \frac{M \times 2.706137}{1.832M + 507}$ where 580 grams is critical mass (U^{235} in sphere)

and $\Delta K = 556 \mu R/gm\ U^{235}$

This value checks the boron bubble experiment and independent calculation[20] mentioned above. See also general discussion

(20) E. Fermi, J. Hinton: Dependence of Reactivity of the Water Boiler on the Mass of U^{235} in the Sphere, LA-470.

for the measurement of K in Chapter 2 of this volume.

(4) Supercritical Behavior of the Water Boiler.[21]

(21) C.P. Baker, F.L. Bentzen, J. Bridge, R.E. Carter, H. Daghlian, H. Hammel, J. Hinton, F. de Hoffman, M.G. Holloway, D. W. Kerst, L.D. P. King, H. M. Lehr, J.H. Midway, R.E. Schreiber, J.W. Starner:"Water Boiler", LA-134.

In order to determine the supercritical behavior of lopo, periods of the boiler where measured for various supercritical control rod positions. In each measurement the intensity was allowed to rise for at least one period and then the increase in counting rate followed for one or more order of magnitude. This procedure gave straight line semi-log plots except for the longest periods. Here the long lived delayed neutrons had not yet reached an equilibrium condition and the final slope of the plots was used for the period determination. Figure 8 shows the degree of criticality in terms of grams of U^{235} as determined from the control rod calibration.

It was thought useful to determine a relation between reactivity and period for the water boiler which might be useful for a higher power boiler. This was done by determining the constants

GRAMS OF U^{235} ABOVE CRITICAL
RECIPROCAL PERIOD (SEC^{-1})
0
0.01
0.02
0.03
0.04
1
2
3
4

Figure 8

in equation (9) below with the data available from the measured supercritical periods, the results of the boron bubble experiment (18.25 = 1 per cent in K) and the known delay periods. (This is equation 9 of Chapter 2 of this volume. A complete derivation of this reactivity equation is given there.)

$$\Delta K = \frac{\tau_o}{T} + \gamma f \sum \frac{q_i \tau_i}{T + \tau_i} \qquad (9)$$

in the limit

$$T \longrightarrow \infty \Delta K = \gamma f \sum \frac{q_i \tau_i}{T} \quad \text{since } \tau_o \sim 10^{-4} \text{ second}$$

or

$$T \Delta K = \gamma f \sum q_i \tau_i = \text{const}$$

Taking the boron bubble result that 548 μRe = 1 gram U^{235} and the supercritical period measurements of Figure 8 we have

T(period)	Grams U^{235} equiv	ΔK in μ Re	TΔK
29.2 seconds	3.97	2176	.064
46.3 "	2.72	1491	.069
101 "	1.52	833	.084
232 "	.78	427	.099
774 "	.24	131	.101
1352 "	.13	71	.096

The last column appears to approach 0.1. The low value for the longest period can easily be accounted for by the uncertainty in the determination of ΔK for such a small change. If one neglects any difference in energy with period for the delayed neutrons $\sum q_i \tau_i$ can be obtained from the known delay periods.

$$\text{delays} = .116e^{-\tau/.61} + .330e^{-\tau/2.2} + .292e^{-\tau/6.5} + .228e^{-\tau/31.7} + .034e^{-\tau/80.3}$$

$$\gamma f = \frac{\Delta K T \infty}{\sum q_i \tau_i} = \frac{0.1}{12.66} = .0079$$

This value for γf, the effective number of delayed neutrons from the water boiler is comparable to the value obtained by other means. (See Section 4.2-3(5) below). All delay amplitudes must be multiplied by .0079 and equation (9) becomes

$$\Delta K \text{ in } \mu R = 10^6 \Delta K = \frac{120}{\tau} + \frac{560}{\tau+.61} + \frac{5730}{\tau+2.2} + \frac{14,990}{\tau+6.5} + \frac{57,100}{\tau+31.7} + \frac{26,800}{\tau+80.2} \qquad (9a)$$

This equation slightly modified, since Snell's orginal delay periods were used instead of the more recent values shown above, was found to be useful and correct when used with the high power water boiler described later. (See Figure 9) Comparing grams of U^{235} from Figure 8 with μRe read from a plot of equation (9a) for the same supercritical periods gives 500 μR per gram of U^{235}. Calculating from boiler cross sections for the condition when the supercritical periods were measured, namely Mc = 577 grams U^{235} and the control rod at 13.24 centimeters

$$K = \frac{M \times 2.563369}{1.832M + (104 + 318)}$$

where control rod section 104 cm^2
sphere and reentrant tube 318 cm^2
422 cm^2

$\Delta K = 508 \mu R$ per gram U^{235}

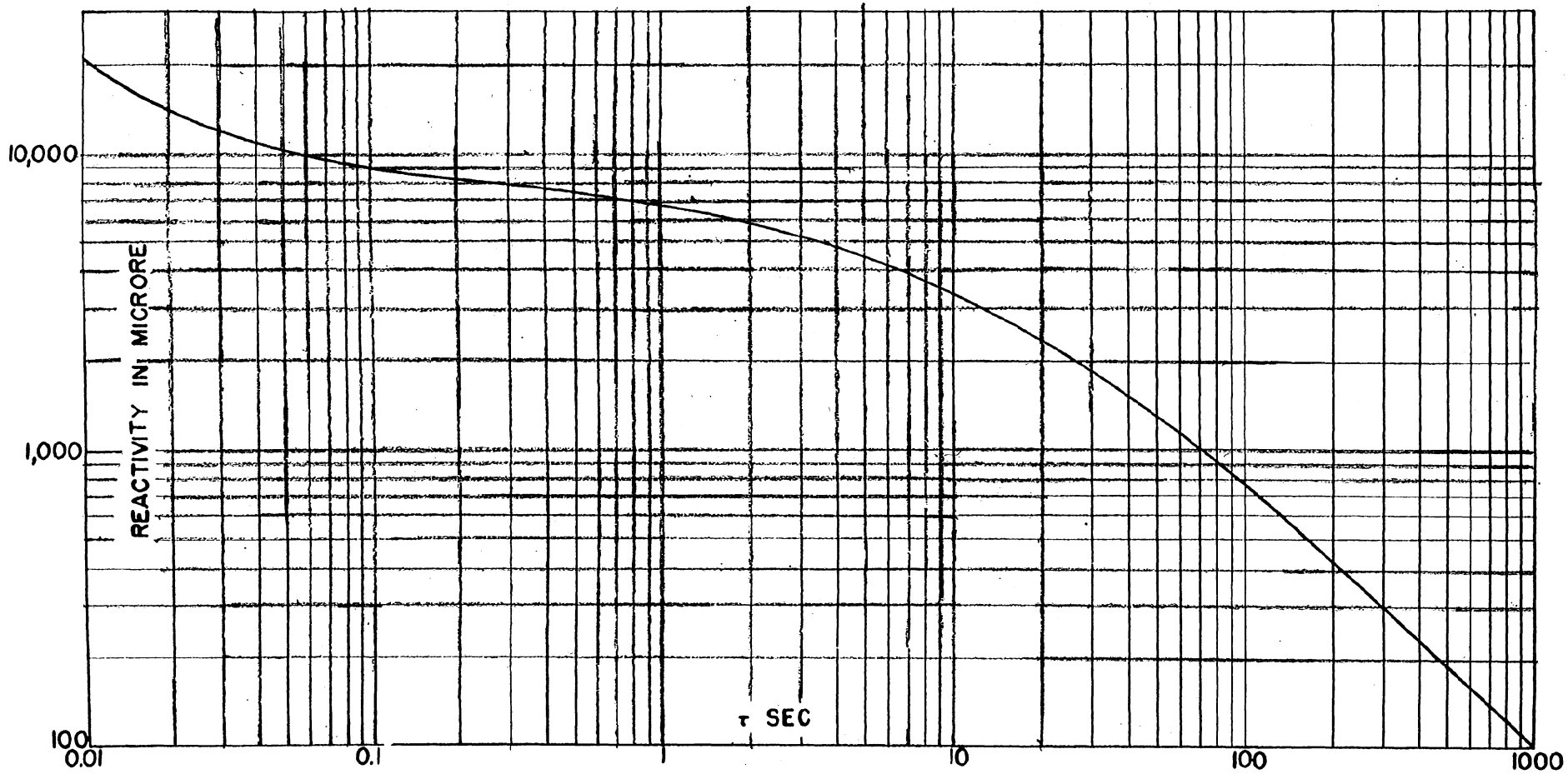
Calculations based on the cross sections of the boiler materials (See also Section 4.2-3(3) above) consistently check those obtained by other means. This gives some confidence to this seemingly rather crude method which has been used in determining the ΔK gram U^{235} equivalence in the high power water boiler.

(5) The effective number (γf) of delayed neutrons and the average prompt neutron period τ_p.[22][23][24]

Figure 9

Reactivity vs period

$$\delta K \times 10^6 = \frac{120}{\tau} + \frac{1000}{\tau + .7} + \frac{32,300}{\tau + 6.5} + \frac{50,900}{\tau + 34} + \frac{16,600}{\tau + 83}$$

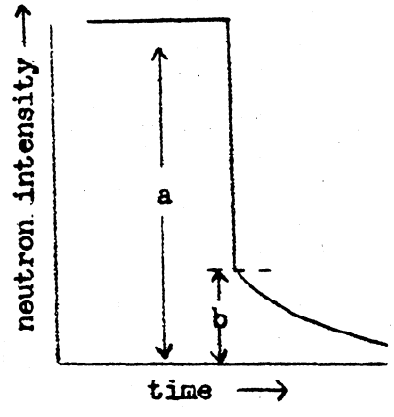


(22)(23) F.L. Bentzen, J. Bridge, F. de Hoffman, D.W. Kerst, L. D. P. King, G. Friedlander: Criticality of the Water Boiler and Dispersion of the Neutron Emission per Fission, LA-183, LA-183A.

(24) F. de Hoffman, S. D. Warshaw, G. W. Weiner: Relative Effectiveness of Delayed Neutrons in the Water Boiler, LA-471.

Several experiments were performed to determine the effective fraction of delayed neutrons, γf; γ is essentially the effectiveness of the delayed neutrons compared with that of the prompt ones and f is the fraction of fission neutrons which are delayed. (See Chapter 2 of this Volume.)

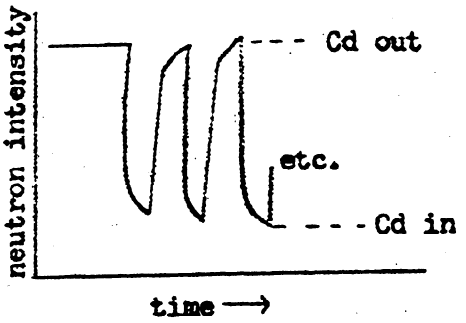
The general scheme for determining γf experimentally was to run the boiler at some level and then to suddenly introduce absorbers so as to shut the neutron intensity off as rapidly as possible. The neutron intensity curve should then look like the accompanying sketch. Here, a, is the initial intensity and, b, depends on the number of delays. Thus a knowledge of b/a should give a measure of γf.



Sketch 1

Several attempts were made to determine a and b. The use of a BF_3 chamber and fast counting techniques gave inconclusive results for b due to the difficulty of extrapolating back to essentially zero time. This difficulty of extrapolation is due to the uncertainty in the short delay components which have been measured to be as short as .4 seconds. Another technique was therefore adopted which essentially eliminates the delay component. A piece of absorber is jerked in and out of the tamper

at such a repetition rate that the delays will not have time to decay and there will be merely a steady background of delays with a rapidly changing prompt neutron intensity superimposed. The fast neutron drop, a-b in the above sketch, will occur in about 10^{-4} seconds for the water boiler. If the repetition rate of the jerked absorber is too high, the neutron level will be unable to follow the absorber and the boiler will lag behind. If the repetition rate of the absorber is too low, the delayed neutrons will not form an average background.



Sketch 2

Sketch 2 shows the neutron intensity as a function of time for an absorber jerked repeatedly at a rate so the delayed neutrons show only a slight decay. From Equation 11 in Chapter 2 it can be shown that for a repetition rate of the required properties, i. e., no log of the boiler and the delayed neutrons forming an average background, the simple result

$$\gamma_f = 1 - \frac{C_o/C_i - 1}{(C_o/C_i - 1)\,K_o + K_o - K_i}$$

is obtained where C_o and C_i are counts on the BF_3 monitor placed in the tamper for the absorber in the "in" and "out" positions respectively and K_i and K_o are the corresponding reactivity of the boiler as measured from the static cd positions (Figure 10). and the absolute boiler calibration determined in section 4.2-3(3). The experimental arrangement is shown in Figure 11. Crank velocities of 20, 155, and 884 revolutions per minute were used. C_i and C_o were measured by scalers 1 and 2, the proper counting times being determined by the photo cell positions which controlled the gate circuits. The positions of the gates were varied

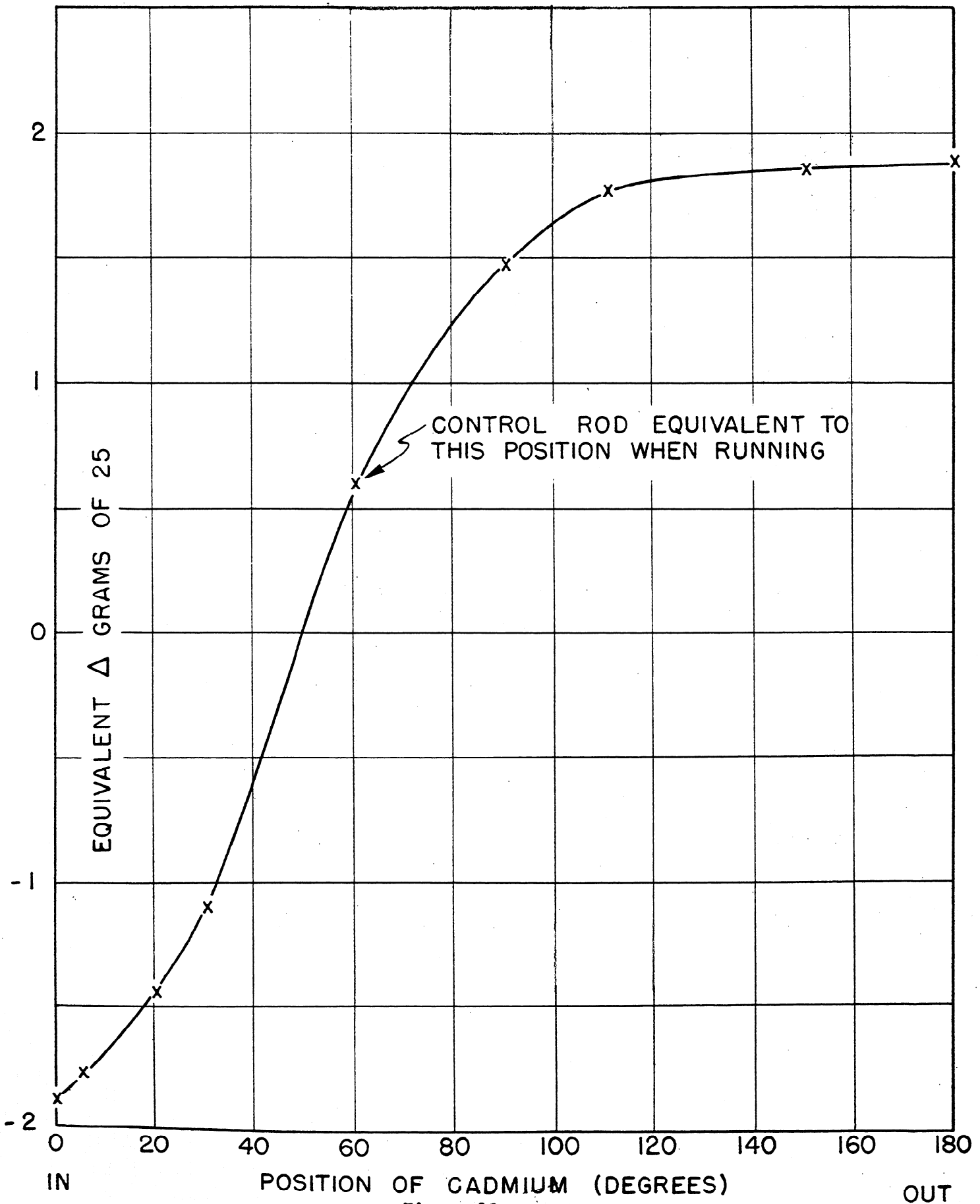


Figure 10

Static Cd calibration

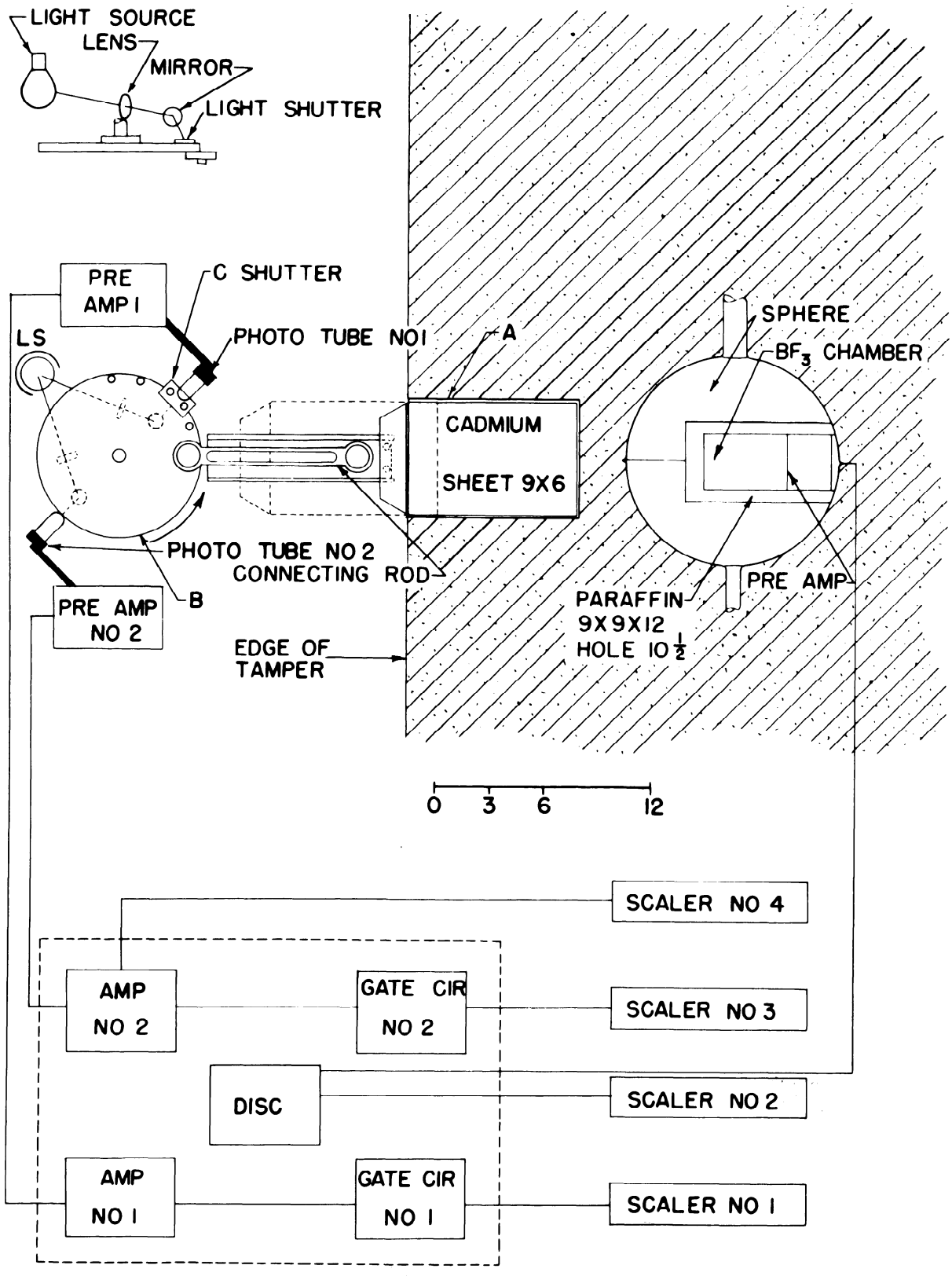


Figure 11

The γ_f and τ_p Experiment

from -90° to $+90^{\circ}$. The ~~rest of the~~ cycle could be obtained by using the reciprocal of the ratio (x) of the counts on scalers 1 and 2 versus phase position. The results for the three crank velocities used are shown in Figures 12, 13, 14. The slowest experimental velocity satisfies approximately the conditions for the equation above and gives a value of $\gamma f = .00822$.

A more complete analysis of the fission process for the case of varying multiplication is calculated[25] (see also equation 14 of Chapter 2.)

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(25) F. L. Bentzen, J. Bridge, F. de Hoffman, D. W. Kerst, L. D. P. King, G. Friedlander: Criticality of the Water Boiler and Dispersion of the Neutron Emission per Fission, LA-183.

Using such an equation two methods for analyzing the experimental data were used (1) Harmonic analysis of the experimental curve using the known relative fractions and periods of the delayed neutrons as determined by Snell and Nagle and (2) a reproduction method where the experimental curves are fitted by assuming values of γf and τ_o until the best fit is obtained. This latter method can be divided into two cases; case I where the repetition rate is high (i.e. the 884 revolutions per minute case) for which $w\tau d \gg 1$ and case II where the repetition rate is such that the delay periods can not be considered a constant and $w\tau d \sim 1$ (i.e. for 20 and 155 revolutions per minute experimental runs).

The harmonic analysis method was used to give approximate values of γf and τ_o and then the more complete reproduction method used to give more accurate values. The 20 and 155 revolutions per minute cases which are insensitive to τ_o, gave an average value

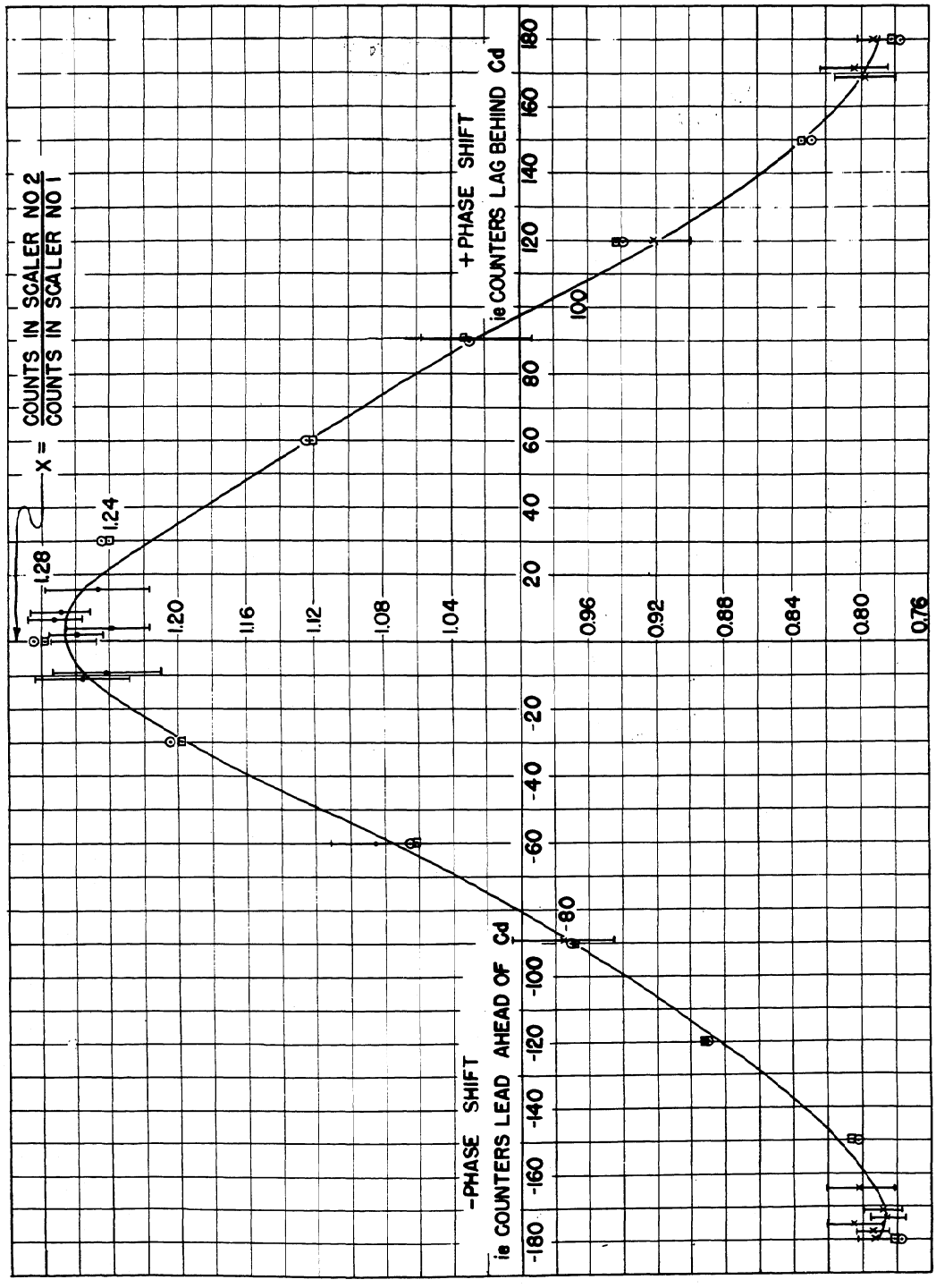

Figure 12

The γf and τ_p Experiment.

20 R. P. M.

Experimental Points

Calculated from Reciprocals from Experimental Points 180° Ahead.

Theoretical Curve Obtained by Use of Reproduction Case II using γf 14.75 Grams Equivalent and Using Snell Delayed Neutron Data

Theoretical Curve Obtained by Use of Reproduction Method Case II Using γf 14.75 Grams. Equivalent and Using Nagel Delayed Neutron Data.

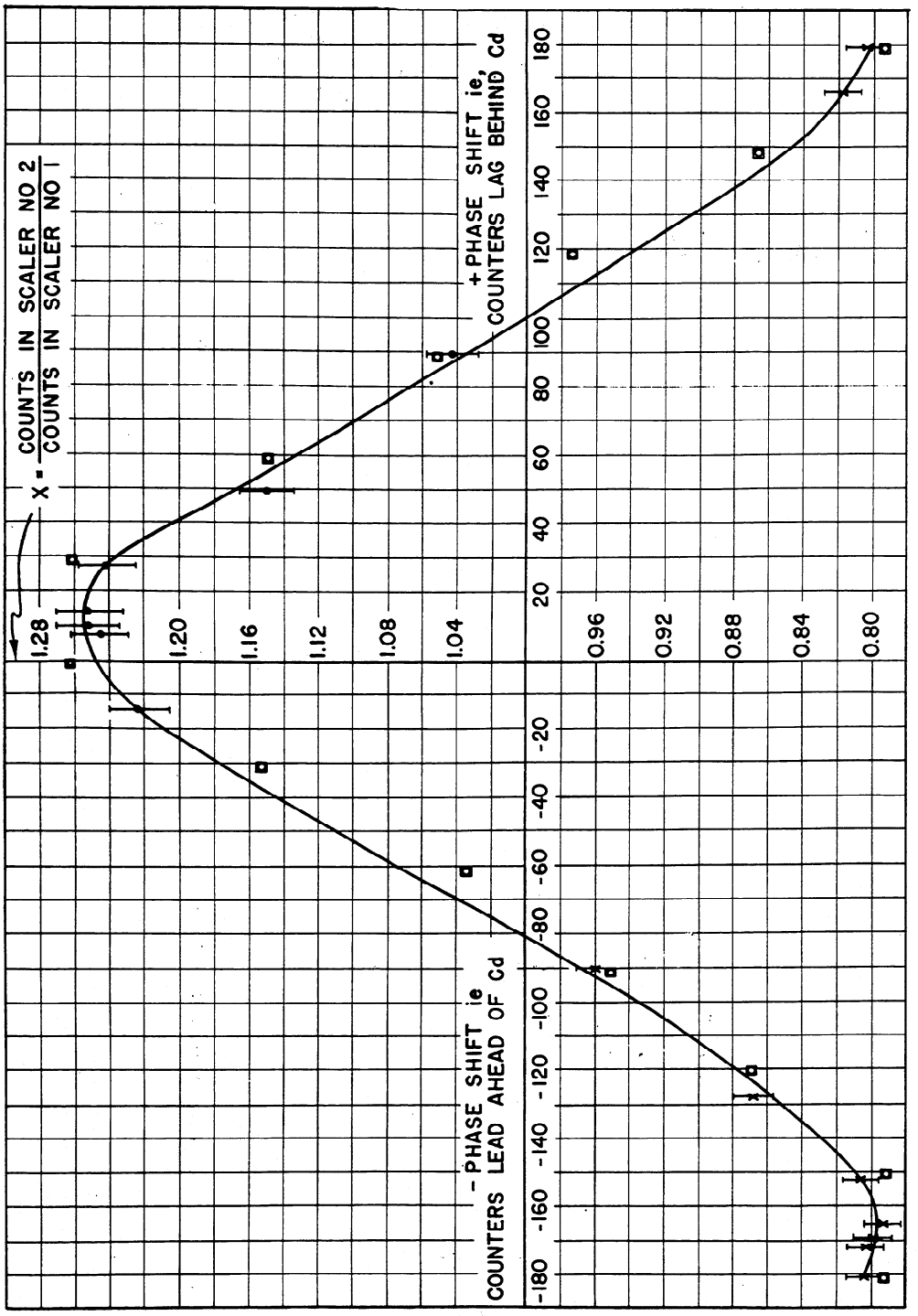

Figure 13

Experimental Points

Calculated from Reciprocals from Experimental Points 180° Ahead

Theoretical Curve Obtained by Use of Reproduction Method Case Using $\gamma f = 14.75$ Grams Equivalent and Using Snell Delayed Neutron Data

Theoretical Curve Obtained by Use of Reproduction Method Case II Using $\gamma f = 14.75$ Grams Equivqlent and Using Nagle Delayed Neutron Data.

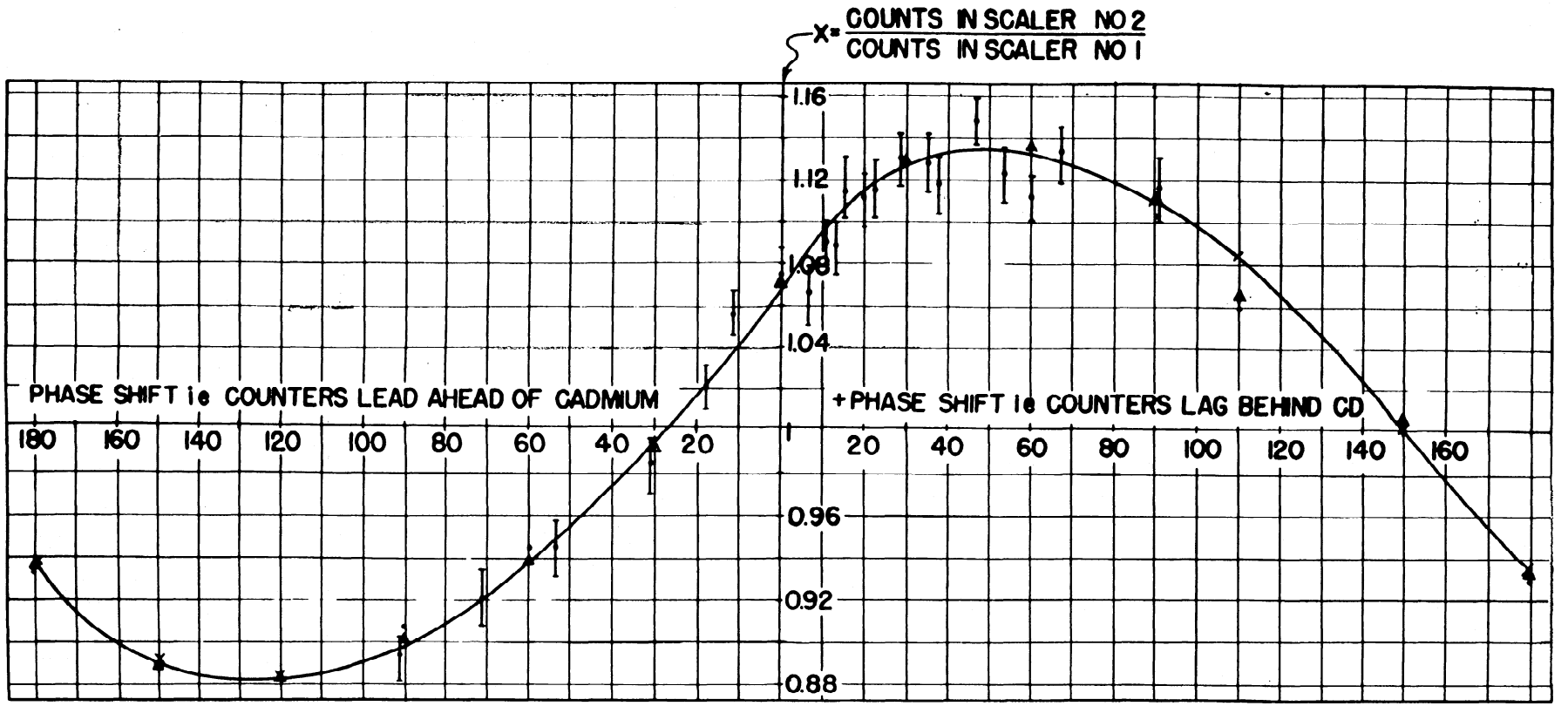

Figure 14

884 R. P. M. curve

I Experimental Points

X Calculated by Reciprocals from Experimental Points 180° Ahead

△ Theoretical Curve Obtained by Reproduction Method Case I Using

δf = 13.27 Grams Equivalent

• Theorectical Curve Obtained by Reporduction Method Case I Using

δf = 14.75 Grams Equivalent.

of .00855 for γf. The 884 revolutions per minute data was found to be quite insensitive to values of γf but due to the large phase lag, τ_o could be determined with some accuracy, Figure 15 shows the result of using different values of τ_o. The best value is $\tau_o = 135$ microseconds and changes of + or - 20 microseconds clearly fall outside the experimental data.

(6) Statistical fluctuations in a water boiler[26][27]

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(26) R. P. Feynman, F. de Hoffman, R. Serber: Statistical Fluctuations in the Water Boiler and the Dispersion of Neutrons Emitted per Fission, LA-101.

(27) F. de Hoffman, R. Serber: Formula for Water Boiler Fluctuations, LA-336.

Short time fluctuations in the neutron intensity of the water boiler were theoretically predicted and experimentally verified on a recording meter as soon as the boiler was put in operation From the Equation 33, Chapter 2.5-7, it is seen that for a number of counts C in a given time interval the expected fluctuations will be given by

$$\frac{\overline{C^2} - \overline{C}^2}{\overline{C}} = 1 + E\,\frac{\chi_2(K^2/\nu^2) + 2K(1-K)}{(1-K)^2}\left[1 - \frac{1 - e^{-|\alpha|T}}{|\alpha|\,T}\right] = 1 + Y$$

where ν is mean value of number of neutrons n emitted per fission

χ_2 is mean value of n(n-1) where n is the number of neutrons emitted per fission

α = decay constant for neutrons

E = counter efficiency

Y = deviation from random error

The above equation is true if the gate width T or time during which counts are taken is small compared to the average delay period, and all the neutrons in the boiler are considered

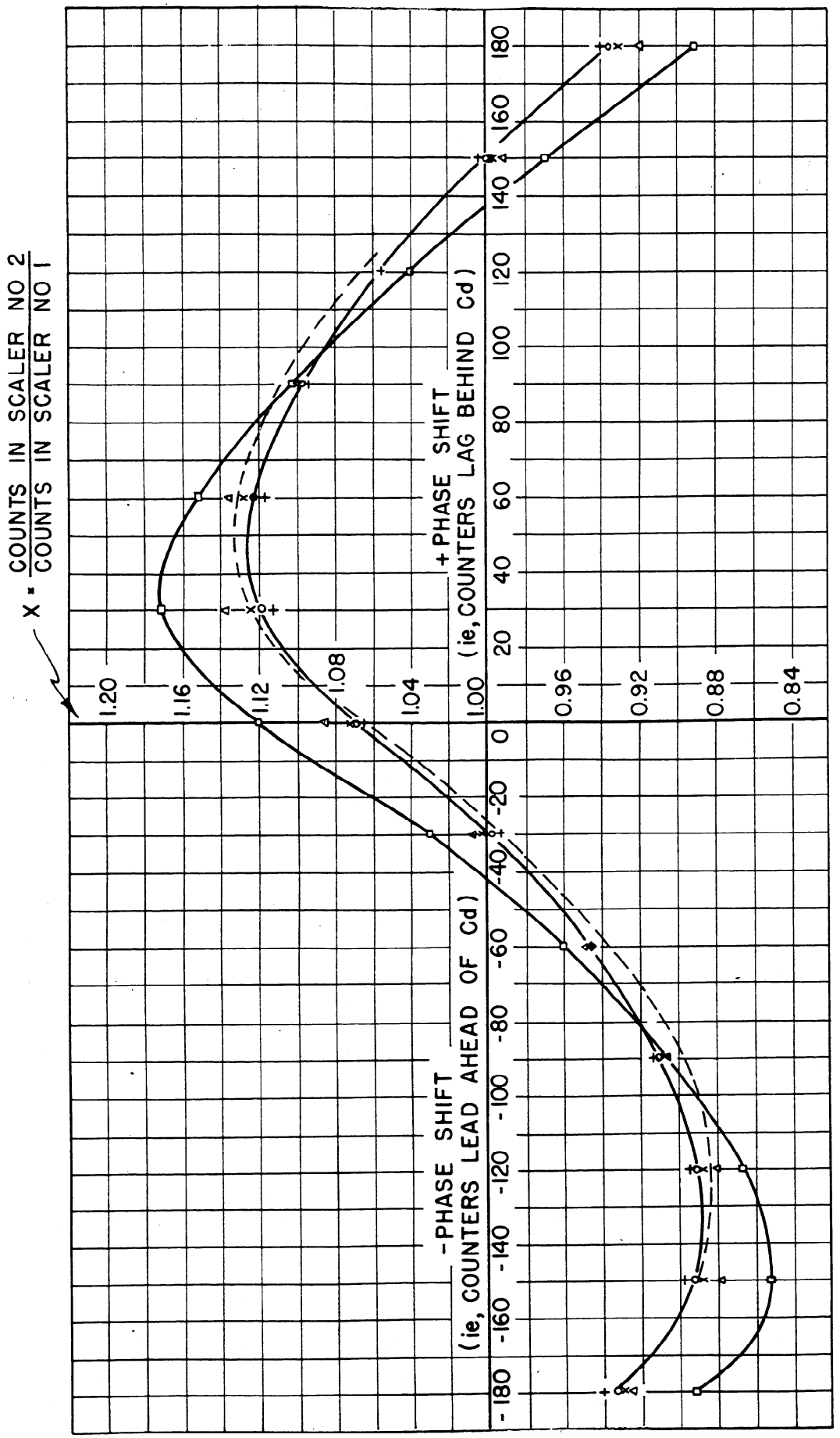

Figure 15

The γ f and τ_p Experiment

884 R. P. M.

+ τ_p = 150 μ sec.

⊙ τ_p = 140 μ sec.

X τ_p = 132 μ sec.

△ τ_p = 120 μ sec.

⊡ τ_p = 90 μ sec.

---- = Experimental Data

equally effective. The gate widths used in the experiment were short compared to the average delay period. The effectiveness of the neutrons depends on the size and symmetry of the boiler and has been shown by Feynman to amount to only a few per cent. A rough estimate from distributions and source effectiveness in the boiler gave 1 per cent correction for this geometric effect.

The left side of the equation would be equal to one for a Poisson distribution of C. The increase in fluctuations observed in the boiler is due to the normal accidental pairs of counts from independent primary source neutrons augmented by 'coupled' pairs of counts which can be traced back to a chain of neutrons originating from a single fission.

It is seen that a large value for the counting efficiency E is advantageous in making the fluctuation term Y large compared to the Poisson term 1. The efficiency of the BF_3 chamber used was 3.69×10^{-4} counts per fission.

Two experimental methods were used to determine the fluctuations, (1) fast film recording of a high speed scaling circuit; (2) electrical gate circuit designed to let pulses through at any desired time for a predetermined time (283 milliseconds in this experiment).

The first method used a large BF_3 chamber coupled to a fast amplifier and scaler. The output of the first scaler unit was connected to the vertical plates of an oscilloscope, a 250 cycle sweep (with several microsecond return) was connected to the other scope plates. The screen was photographed by film moving continuously at 100 feet per minute.

This method permitted a single strip of film to be analyzed for various gate widths. This was only possible for comparatively short gate widths unless an excessive amount of film had been used. For this reason the electrical method was used to determine the long gate widths. 2200 individual gates were taken over a period of 12 hours. These were broken down into 76 small sets of from 10 to 50 gates each to avoid any large fluctuations in $\bar{C}$ during any one set.

The best value for Y is $4.17 \pm .16$ showing that the fluctuations in counts are considerably larger than for a Poisson distribution.

(7) Neutron distribution measurements[28][29][30]

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(28) J. Hinton, L. D. P. King, R. E. Schreiber, J. W. Starner: Distribution and Power Measurements in the Water Boiler, LA-152.

(29) R. E. Carter, J. C. Hinton, L. D. P. King, R. E. Schreiber, J. W. Starner: Water Tamper Measurements, LA-241.

(30) E. Greuling: Graphical Method of Obtaining Critical Masses of Water Tamped Water Boilers, LA-493

The neutron flux for the boiler at critical was measured as a function of radial position in the sphere as well as in the tamper. Thermal fluxes were determined by using calibrated manganese foils and a small fission chamber with a known amount of U^{235}. Fast neutron fluxes were measured with a fission chamber containing a known amount of U^{238}.

Plugs of 1 inch diameter or special 3 inch x 3 inch x 6 inch tamper blocks could be removed so that detectors could be placed at any desired radial position.

For measurements made inside the sphere it was necessary to use thimbles or reentrant tubes placed in the level indicating tube of the sphere. See Figure 2. This is necessary due to the

corrosive action of the solution and the need of avoiding evaporation or contamination of the solution. Four different reentrant tubes were used to accommodate the different size chambers.

All thimbles were made of 1/32 inch wall stainless steel tubing except for a special .005 inch wall stainless steel sheath. This sheath was designed for use with the Mn foils to give a minimum distortion to the true distribution. Distortions in distribution caused by the thimbles were absorption in the walls, leakage path out thru the tamper, and displacement of active solution. An additional distortion is produced by the level indicating tube containing solution and extending thru the tamper.

The results of the Mn foil (7/8 inch x 1½ inch x .006 inch) measurements are shown in Figure 16. Curve (I) taken in a 1/32 inch wall keyhole shaped tube with a 7/16 inch I. D. circular hole and 1/16 inch slot (made to accommodate a source, fission chamber or foils). This does not give the true distribution for the reasons given above. Bombarding times varied from three to five minutes in the sphere and from five to ten minutes in the tamper with the boiler running at about 3 milliwatts. Since 15 to 20 seconds was required to insert the foils to the bottom positions of the long 5 mil sheath, the boiler intensity was reduced by a factor of six with the safety rod while the foils were put in or taken out.

The solid line of Curve II inside the sphere is the theoretical curve and the dots the experimental points obtained in the .005 inch sheath. Distortions produced are extremely small due to the thin walls and small sectional area of the sheath. Any

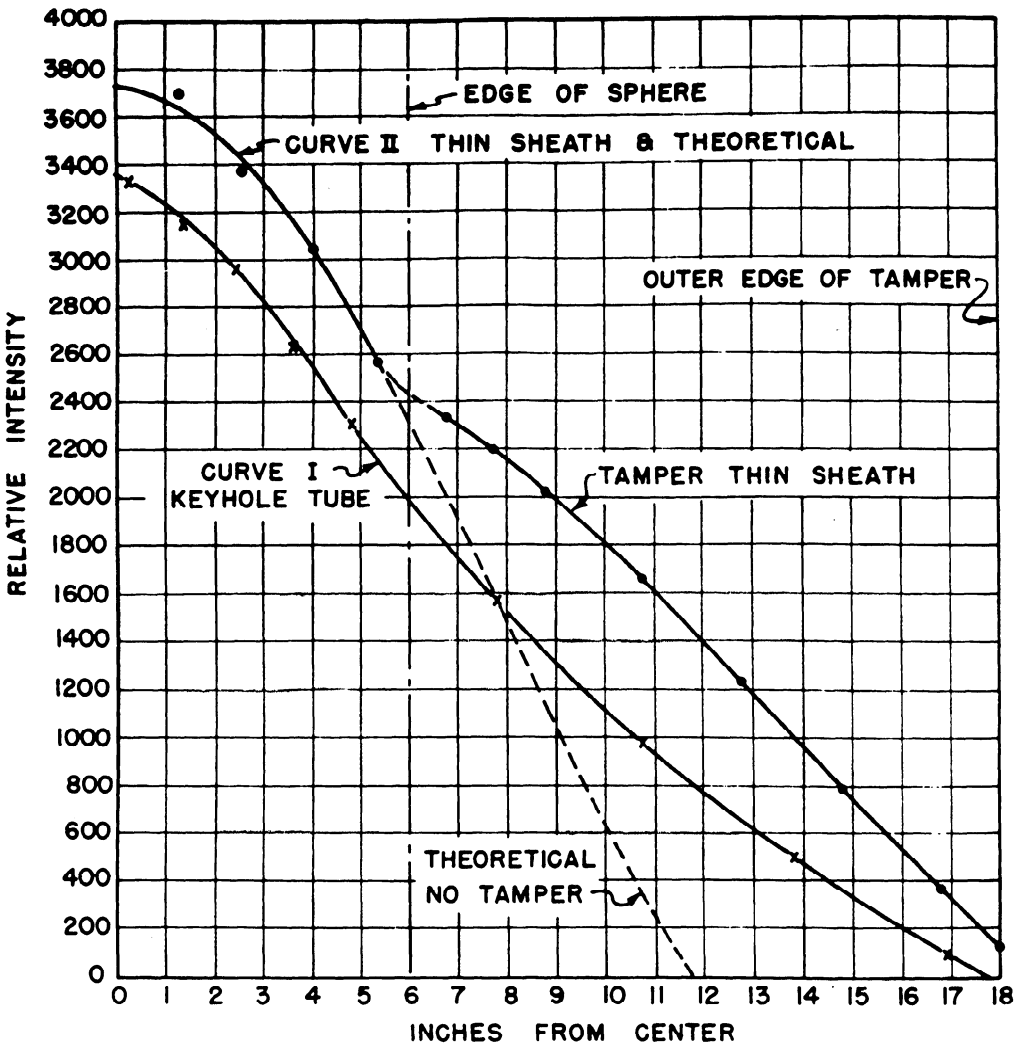

Figure 16

Neutron distribution in Water-Boiler. Mn-foil data.

effect of the level indicator tube or the dumping pipe was eliminated by curving the sheath and running it at right angle against the bottom of the sphere at a point several inches from the emptying pipe. Measurements were then made in the lower half of the sphere. The tamper readings were made in a 1/16 inch crack between bricks both with and without a .005 mil sheath. The effect of this sheath could not be detected. The ordinates of Figure (16) representing the saturated foil activities A_s have been raised by 4.4 per cent and those in the tamper by 1.4 per cent for calculated foil and sheath depressions. The foils were calibrated in a standard geometry after the distribution measurements were made, the absolute neutron density being given by $A_s/4820$ if A_s is measured in units of 64.

For critical conditions the equation for the neutron distribution of an untamped sphere as a function of radius r is of the form Sin Kr/r where $K = \pi/R$ and R is the radius of the untamped sphere. The distribution in a tamped sphere should be the same as that in a somewhat larger untamped sphere almost to the tamper boundary due to the short diffusion length in the solution. Since the sphere part of Curve II is indistinguishable from the theoretical curve, the dotted portion giving the critical radius (R=29.8 centimeters) of an untamped sphere should be quite good.

The shape of Curve II (Figure 16) in the tamper agrees with that calculated[31] for a somewhat smaller sphere. A discontinuity

(31) R. F. Christy, Unpublished.

at the sphere tamper interface is to be expected due to the change of medium and the absorption by the stainless steel walls of the

sphere. The slight hump in the tamper was predicted because of the creation of thermal neutrons in the tamper by the slowing down process. The experimental curve in the outer portion is linear and shows an appreciable intensity to the outer edge, while the theoretical curve is exponential and drops essentially to zero at the edge. This difference along with the large value of R obtained above seems to indicate that the BeO tamper was even more effective than calculation predicted.

Results obtained with a small U235 chamber were in good agreement with the foil data after corrections were applied for the various sources of error described above. The chamber dimensions were 5/16 inch aluminum cylinder 1 9/16 inch long. (Constructural details of this chamber and the spiral type U235 chamber used for the fast neutron measurements are described in Volume I, Chapter 2 of this series).

Figure 17 shows the results of measurements of the fast neutrons with the U238 chamber. As indicated on the graph, tamper measurements were made in a $1\frac{1}{4}$ inch reentrant tube and in the 1 inch hole; these were arbitrarily normalized at one point. The difference in the two curves is probably due to the distortion produced by the large reentrant tube and the difference in tamper thickness in the two directions.

Distribution measurements were also made during the water tamper tests. (See nest section). Data were taken with the Mn foils, the U235 chamber and the U238 chamber described above. The sphere contained 717 grams of U236 and a 200 mc Ra Be source in the center during the measurements. The results of the foil data are shown in Figure 18.

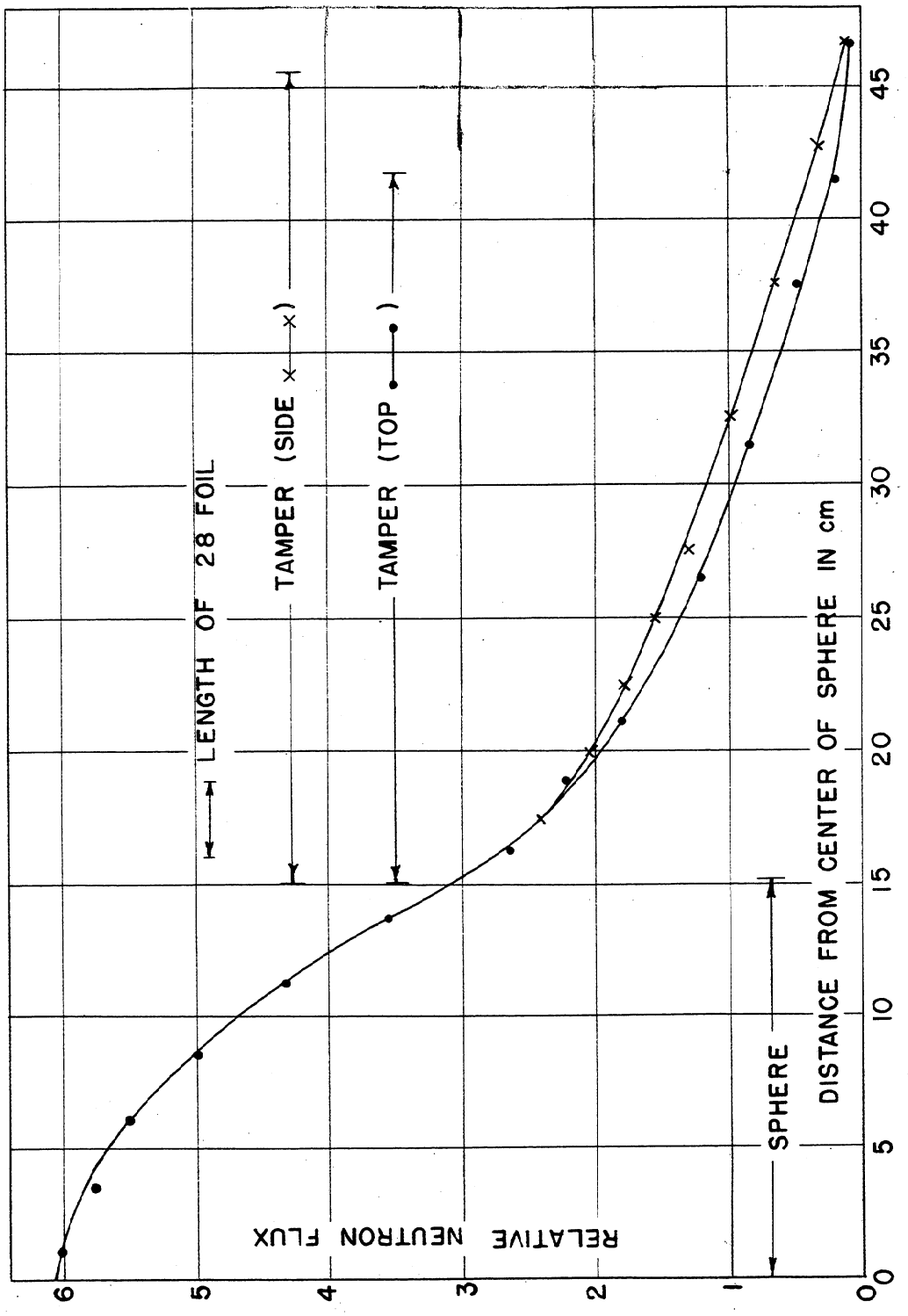

Figure 17

Neutron distribution by U238 Chamber

* •—• As measured in 1½" Reentrant Tube

* ×—× As measured in 1" Hole in BeO Tamper

* Normalized at 17.4 centimeter.

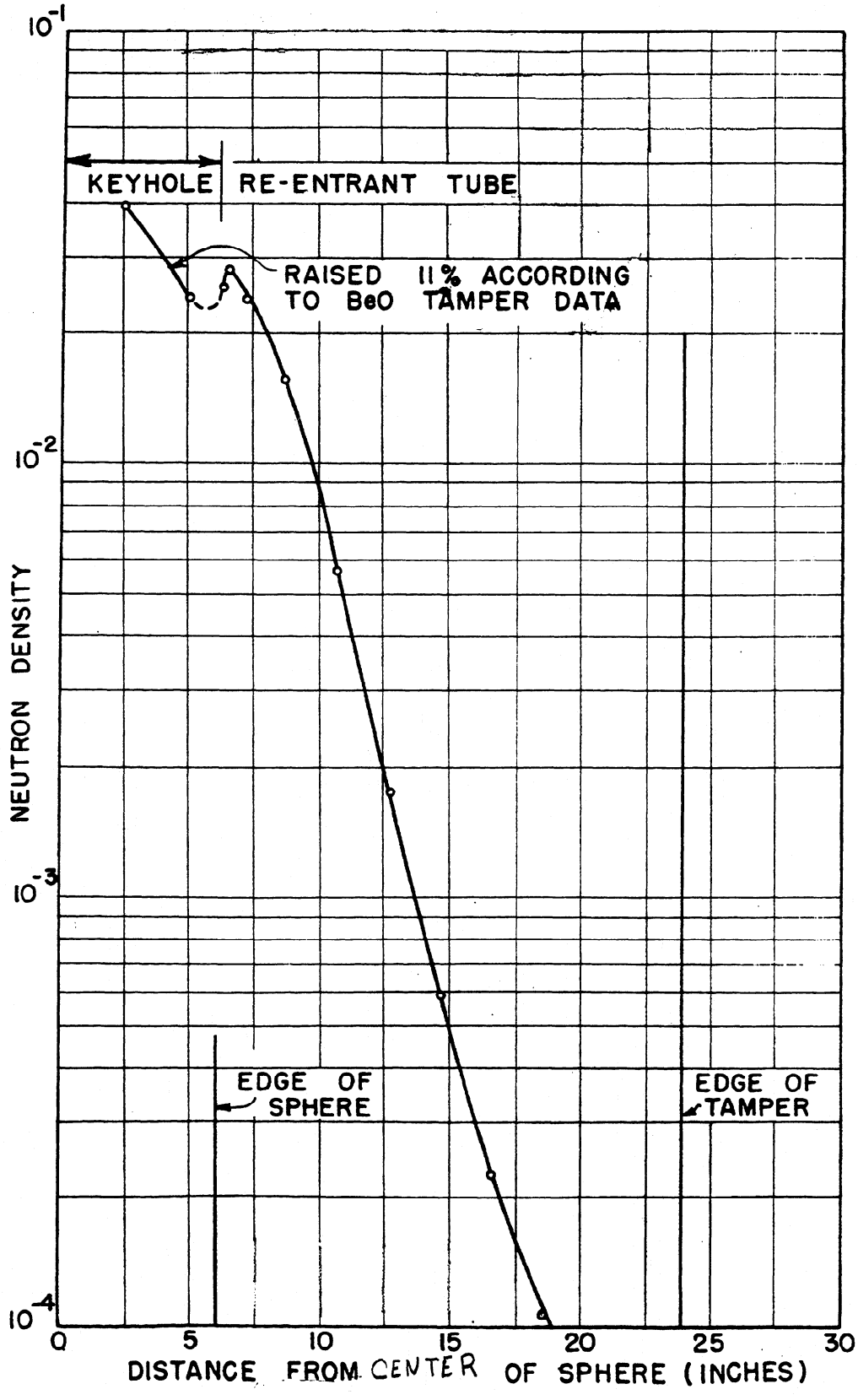

Figure 18

Mn Foil Distribution - water tamper.

The five mil sheath was used for the data in the tamper while the sphere measurements were made with a 1/32 inch wall re-entrant tube. The latter results were corrected by the factor determined in the BeO tamper distribution measurements. A considerable depression in the thermal neutron flux is seen to exist at the sphere tamper boundary.

The results of the U235 chamber showed a similar depression at the sphere tamper interface. Except for this boundary distortion the results gave a straight line on the semi log plot given by $e^{-X\ cm/507}$.

The BF_3 chamber and the U^{238} chamber gave similar results which can be expressed as $e^{-X\ cm/4.6}$ and $e^{-X\ cm/5.37}$ respectively.

Estimates of the power of lope were made using a small U^{235} fission chamber and independently with calibrated manganese foils.

Power in watts = $\frac{N\sigma\overline{n\nu}}{3 \times 10^{10}}$ where N and σ refer to U^{235}. The counting rate of the chamber depends on the efficiency, flux through the chamber and total cross section for the U^{235} in the chamber. The efficiency was calculated from the known thickness of the foil and chamber geometry; the mass of U^{235} in the chamber is also known. The average value $\overline{n\nu}$ of the neutron flux obtained from the distribution curves gives $\overline{n\nu} = .76n\nu$. The power results of the foils for which $\overline{\nu}$ is taken to be 2.2×10^5, and those of the chamber agreed within 9 per cent of each other.

(8) Tamper tests(32)(33)

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(32) R.E.Carter, M.G.Holloway, D.W.Kerst, R.E.Schreiber: Tamper Tests in Water Boiler, LA-105

(33) R.E. Carter, L.D.P.King, R.E.Schreiber, J.W.Starner: Tamper Tests, Unpublished.

Experiments were performed to determine the effectiveness of various substances as possible tamper materials.

Two general types of tests were made:

(a) A single radial course of BeO bricks were replaced by a different material of equal volume[34]. It was not expected that this technique would give exact data for complete tampers, but it was hoped that relative magnitudes of the effect of each material could be obtained. The boiler was never far from critical for these measurements and hence quite sensitive to small changes in tamper. The results of these tests can be subdivided into two groups (a) the total neutron effect, (b) the epithermal neutron effect obtained by enclosing the bricks entirely in 30 mil cadmium before placing them in the tamper. Two liquids and powdered WC were measured in an aluminum container; the sink effect of the container being corrected for by testing it in the normal BeO tamper.

This general type of measurement was done in two ways. Samples not too different from BeO could be measured by moving the control rod to the proper position to maintain the boiler at critical. Samples which had a large effect by themselves or when placed in the cadmium box were measured by determining the multiplication of a Ra Be source. The geometry of the boiler and detector was identical to that used in the approach to critical measurements. The same curve of reciprocal count versus mass of U^{235} in the sphere could therefore be used to obtain the equivalence in grams U^{235} of the tamper samples being tested.

Table 4.2-3A tabulates the results of these measurements. The

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(34) R. E. Carter, M. G. Holloway, D. W. Kerst, R. E. Schreiber: Tamper Tests on Water Boiler, LA-105.

TABLE 4.2-3 A

Tamper Tests

Material	Grams of U^{235}	
	Total Effect	Epithermal (in Cd)
BeO	0	0
C	1.52	.67
D_2O	1.93	.9
Pb	2.67	.5
Bi	2.74	.85
Oak	5.0	5.8
H O	5.3	4.8
Paraffin	7.0	8.7
Air	8.0	4.8
Cu	11.9	.5
Fe	12.7	.6
Wc	15.79*	3.8***
	14.8 **	
Tu	- 4.54	.6

* Density - 4.91
** Density - 14.8 (solid)
*** Density - 5.56

TABLE 4.2-3 B

Material	Size of Tamper	Critical Mass Grams U^{235}
BeO	3 ft. mock sphere	572 - 2*
BeO - graphite	2 ft. BeO cube surrounded by 1½ ft.of graphite shell	573 - 2
Graphite - BeO	18" graphite cube surrounded by 1 ft. of BeO shell	735 - 10
Graphite - tuballoy slugs	4 ft. cube of graphite and 20 slugs of tuballoy 2¼" in diameter, 2¼" long placed 12 cm. from edge of sphere	740 - 10
Graphite	4 ft. cube graphite	760 - 10
H_2O - tuballoy slugs	5 ft. diameter cylinder, 5 ft. high with 63 tuballoy discs 2¼"x 2½" spaced equally on a spherical surface 20 cm. in radius	1100 - 100
H_2O	5 ft. cylinder, 5 ft. high	1200 - 50

* Measured with U238 chamber in tamper and reentrant keyhole tube

effect of the various materials tested is expressed as ΔM. This indicates the amount of U^{235}, either positive or negative, which would have to be put in the sphere to make the boiler just critical when the normal 3 inch x 3 inch x 12 inch BeO bricks, extending from the sphere to the edge of the tamper, are replaced by the sample in question. The tuballoy bricks contained about 220 grams of U^{235}; this was estimated to be equivalent to about 4 grams in the sphere itself so presumably accounts for the negative ΔM in the table.

(b) The second general type of tamper tests consisted in replacing a large portion of, or the entire BeO tamper(35). The materials

(35) R. E. Carter, L. D. P. King, R. E. Schreiber, J. W. Starner: Tamper Tests Unpublished.

tried were pure graphite, a combination of BeO and graphite, graphite supplemented with tuballoy slugs, water, and water with tuballoy slugs. The results are shown in Table 4.2-3B. The measurements were made in the hope of finding a possible tamper for the high power water boiler with more suitable neutron properties than the BeO. The objection to this tamper material is the Be(γ-n) reaction in providing a variable driving source dependent on past running history. This is objectionable if sensitive critical measurements are to be made.

In all cases except the BeO core graphite shell combination insufficient U^{235} was available to actually go critical. The technique used in the approach to critical was therefore used. The critical mass was estimated by measuring the counting rate of various detectors as a function of the mass of U^{235} in the sphere when using a 200 mc. Ra Be driving source. This method

of measurement becomes more and more uncertain with the length of the extrapolation required to reach the critical condition. A four foot cube of graphite was first tested with four approximately equal additions of U^{235} which broughtthe total from 580 grams to 663 grams of U^{235}. Internal manganese foils were placed in the position found to give a linear reciprocal count versus grams of U^{235} plot in the original approach to critical measurements.

The data for the graphite again gave a linear plot so that the extrapolation (about 90 grams equivalent) gave a reliable critical mass of 760 grams for a pure graphite tamper.

In order to reduce the amount of U^{235} required with a graphite tamper a suggestion of Mr. Fermi's was tried. Twenty $2\frac{1}{4}$ inch x $2\frac{1}{4}$ inch tuballoy cylinders were placed in a lattice arrangement 12 centimeters from the sphere. This lattice gave only a slight improvement estimated to be about 20 grams U^{235} equivalent. Shifting the slugs to a distance of 8 centimeters from the sphere was slightly less effective (14 grams of U^{235}) than at the 12 centimeter distance. Due to the small effect of the slugs no measurements at distances greater than at the 12 centimeter distance from the sphere were made.

As a mock up for a bismuth core BeO shell tamper an 18 inch cube graphite core backed by 1 foot of BeO was tried. If the critical mass was suitable the bismuth shell would act as a gamma ray shield between the sphere and the BeO. This arrangement was better by 24 grams of U^{235} than the pure graphite.

Critical mass measurements were made in water for several reasons (1) to check theoretical methods developed to calculate neutron

behavior of water, (2) to determine safe amounts of U^{235} which could be handled in processing and (3) to see if water was a suitable material for a high power boiler.

The BeO tamper was replaced by a 5 foot diameter cylindrical water tank 5 feet high. This was effectively an infinite tamper due to the short diffusion length of thermal neutrons in water. Since only a limited amount of U^{235} was available(717 grams at the time) it was expected that criticality would not be reached and the extrapolation method would have to be used. Detectors were placed in the following positions, distances being measured from the center of the sphere to the center of the detector; a BF_3 chamber at 18 inches, Mn foils in a re-entrant tube at 2 7/8 inches and 4 7/8 inches, a small U^{235} fission chamber at 2 7/8 inches. Concentrations of 400, 505, 610, and 717 grams of U^{235} were used in the sphere. These detectors were the same ones used in the original approach to critical measurements; their locations were also quite similar to those used at that time. This was fortunate since the critical mass for water turned out to be about 1200 grams of U^{235}. Since only 717 grams of U^{235} were available this necessitated a long extrapolation. The similarity in these curves to those obtained earlier gave some confidence in this long extrapolation. Following a suggestion of Mr. Teller 63 tuballoy discs (either 2.25 inches or 2.50 inches in diameter and 0.7 inches thick for a total of 50 kilograms) were equally spaced on a spherical surface of 20 centimeter radius. Two concentrations of 610 and 717 grams of U^{235} were used. The results obtained by some of the detectors were rather inconclusive probably due to the distortion produced in the distribution by the slugs. In general

the data indicated very little if any gain.

4.3 HIGH POWER WATER BOILER (HYPO)

4.3-1 Design Considerations

(1) General description.

The primary purpose of the high power water boiler was to furnish a useful tool for research purposes requiring a large neutron flux. An enriched pile similar to the low power water boiler seemed ideal for such purposes due to its compact size and high attainable flux.

A power of one kilowatt was seletced as the basis for the final design. This power was believed attainable with the limited amount of enriched material available at this time; the cooling requirements would be simple, the chance of trouble from frothing or large gas evolution due to electrolysis of the solution would be small, and a reasonably high flux of 5×10^5 neutrons per square centimeter seconds was expected.

The general design of the reactor was influenced by that of the low power boiler. Some modifications were made, however, independent of the new design features necessary for higher power operation. The principal modification was to eliminate the hydrostatic control and poor geometry storage system used for lopo due to the experience gained in the behavior of enriched Uranium in water solutions.

The added design features required for increased power operation were numerous: (1) A change of solution from Uranyl Sulphate to Uranyl Nitrate was made to permit the extraction of fission fragments by a known method (ether extraction); (2) installation

of additional control rods for greater flexibility of operation; (3) introduction of an horizontal one inch pipe or "glory hole" through the sphere to permit access to the highest neutron flux for certain types of experiments; (4) introduction of water cooling and air flushing systems; (5) construction of gamma ray and neutron shields; (6) the addition of a graphite thermalizing column; (7) use of 1/16 inch instead of 1/32 inch stainless steel throughout as a precaution against possible increase in corrosion when operating at high power.

The general hypo layout is shown in Figure 19. The arrangement is such so as to permit unobstructed paths of at least 30 feet for neutron beams from the thermal column or ports leading to the reactor. Water, air and solution drain pipes are in a shielded underground trench leading to the small chemistry lab and decontamination equipment.

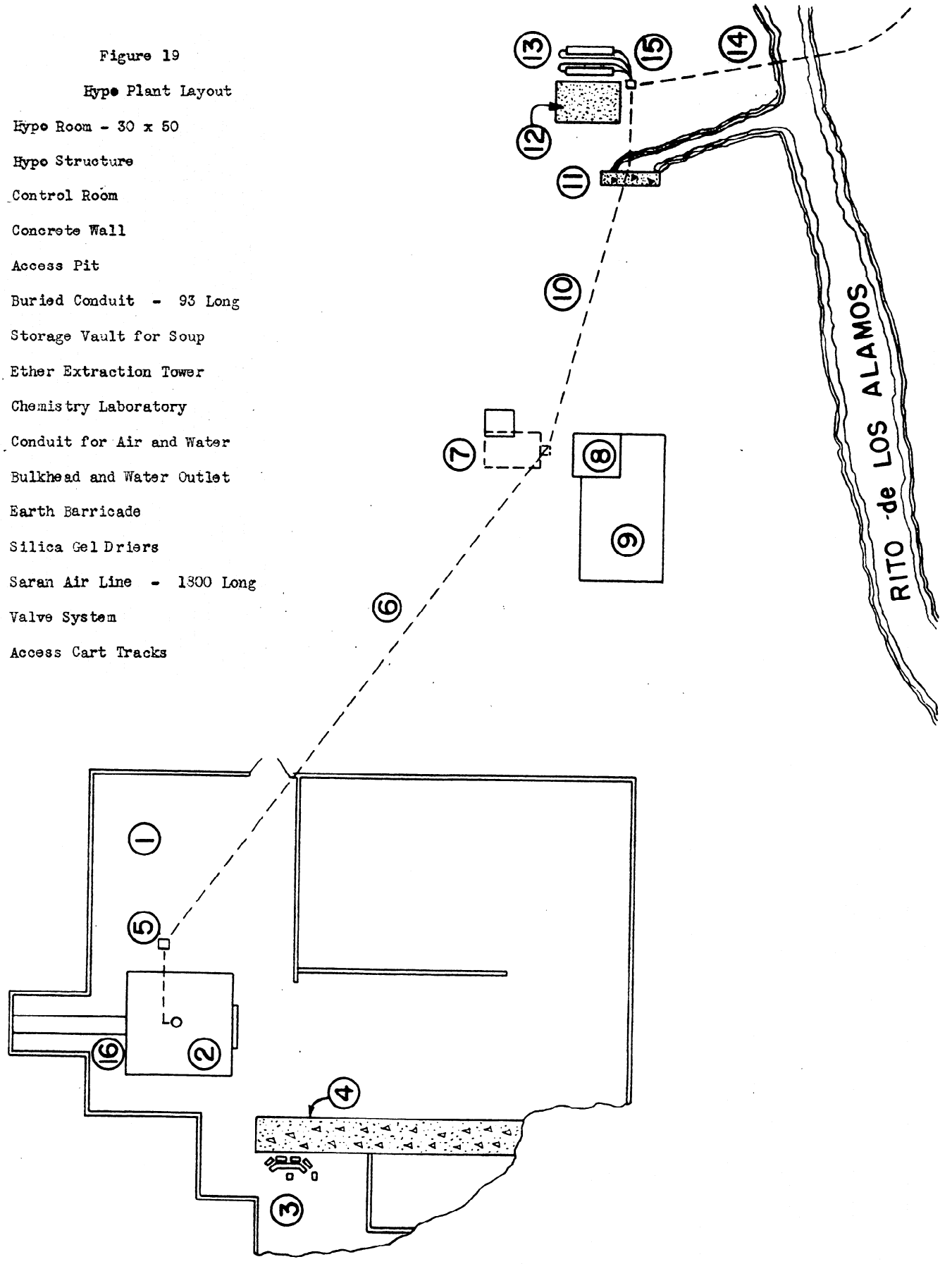
When the high power boiler was planned, it was thought advisable to have facilities available for decontaminating the solution. This was believed necessary in case conditions should arise which would require the quick return of the material for other purposes, and in addition the length of time the boiler could run without requiring decontamination was somewhat uncertain. For these reasons a small chemical laboratory was constructed with a fractionating tower and other equipment necessary for decontaminating the boiler solution which might have several thousand curies of activity.

The ether extraction method was chosen for decontamination since the method was well known for purification of uranyl nitrate. The flow sheet for the equipment is shown in Figure 20. The details

Figure 19

Hypo Plant Layout

1. Hypo Room - 30 x 50
2. Hypo Structure
3. Control Room
4. Concrete Wall
5. Access Pit
6. Buried Conduit - 93 Long
7. Storage Vault for Soup
8. Ether Extraction Tower
9. Chemistry Laboratory
10. Conduit for Air and Water
11. Bulkhead and Water Outlet
12. Earth Barricade
13. Silica Gel Driers
14. Saran Air Line - 1300 Long
15. Valve System
16. Access Cart Tracks



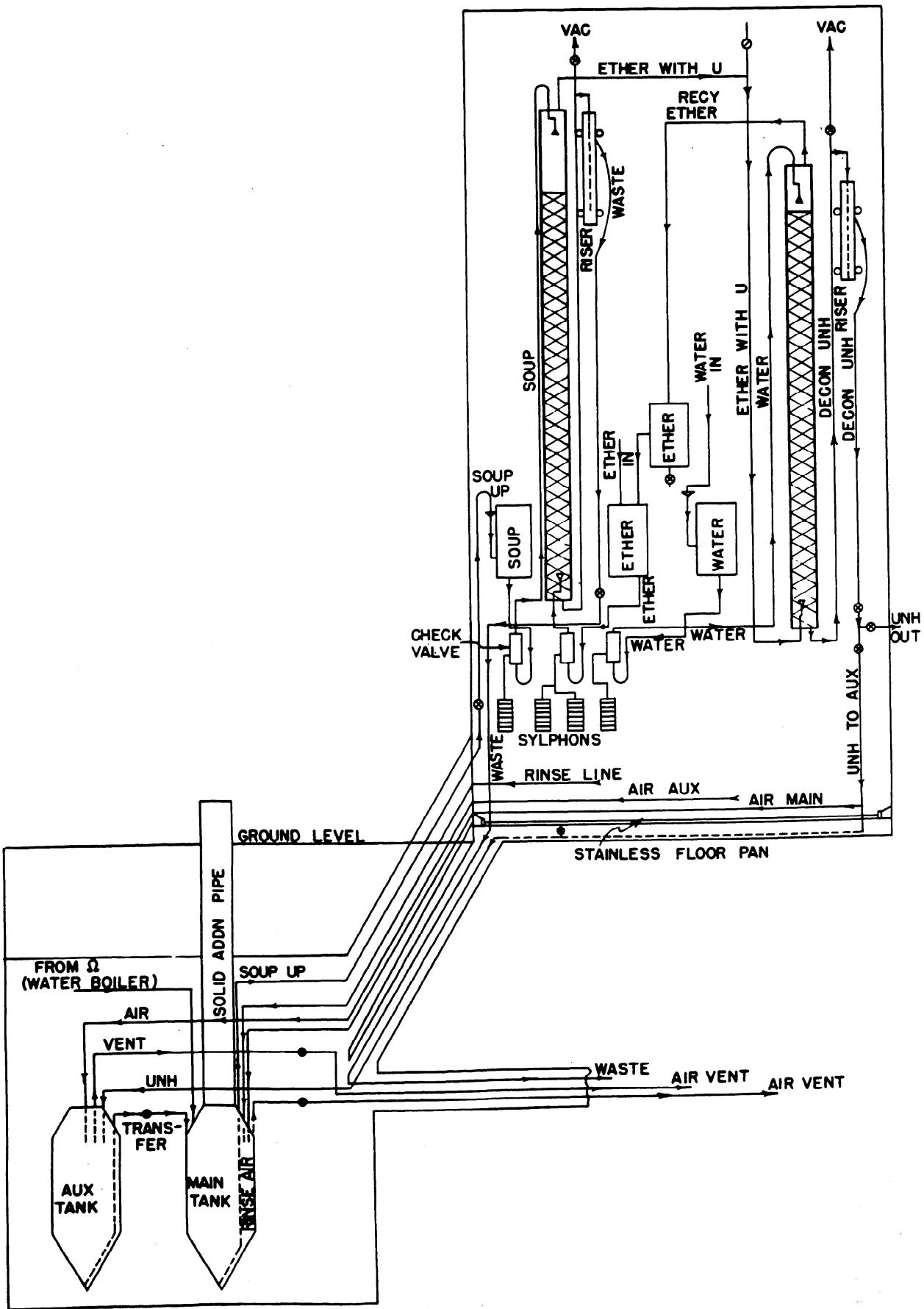


Figure 20

Ether extraction system - Omega - Qualitative flow sheet.

of the equipment and method are given in reference(36) and Volume VIII, Chapter 7 of the Los Alamos Technical Series.

(36) L. Helmholtz, J. C. Nevenzel, P. H. Watkins: High Power Water Boiler (sections on decontamination) LA-394.

It now seems that such elaborate equipment may not be needed for a water boiler since there has been no need for decontamination of the solution in over 2500 kilowatt hours of operation. This is due to the extremely low corrosion rate of the stainless steel container and the large fraction of fission activity (an estimated 30 per cent) carried out by the flushing air.(37)

(37) A. Goldstein, S. Katcoff: Sweeping of Gases from Homogenous Pile, LA-548.

(2) Critical mass estimate from lopo measurements

It was possible to get a rather good estimate of the amount of U^{235} which would be required for the high power boiler from simple calculations based on measurements made on lopo. Various tamper measurements have been described (Section 4.2-3, (8b).) These showed that the most effective tampers were BeO or a composite BeO core graphite shell. It was pointed out there, that beryllium is not an ideal tamper material for certain types of experiments due to its large γ - n cross section. The need of BeO bricks for other high priority experiments going on in the laboratory, and the amount of enriched material available lead to the choice of the composite tamper irrespective of other considerations.

Numerous other critical measurements were made to assist in estimating the critical mass required for lopo. The effect

of a 1/32 inch thicker sphere wall was measured by fitting a spare hemispherical spinning around the lopo sphere; the effect of the cooling pipe was estimated by placing a short section of the pipe at various positions inside the sphere; a similar experiment using reentrant tubes determined the effect of the "glory hole".

In all these measurements the change in control rod necessary to hold the boiler just critical gave a measure of the equivalent grams of U^{235} for each sample tested. The net result of these additional absorbers was determined as 130 grams U^{235}. (Thicker sphere 20 gram, cooling pipe 80 gram, glory hole 30 gram).

In making these estimates it was assumed that the effect of these absorbers was additive and that one could extrapolate the effect of a small absorber to one many times larger as was the case for the cooling coil. These assumptions are not necessarily true, but the results proved to be quite accurate.

The conversion from uranyl sulphate to uranyl nitrate should decrease the reactivity by about 3.4 per cent due to the larger nitrogen cross section (1.75 barnes instead of .5 barnes for sulphur). The absolute calibration of lopo (section 4.2-3c) established that 1 per cent in K was equivalent to 18.2 grams of U^{235}. This meant that a change from sulphate to nitrate was equivalent to about 70 grams.

The temperature coefficient should be about proportional to the amount of uranium in solution so was estimated to be 9 grams per degree C instead of .55 grams per degree C measured for lopo (Section 4.2-3(2).)

The total estimated critical mass, from the solution and structural changes, amount to 205 grams more than for lopo, or a total of 770 grams. This increase consisted of (1) 70 grams for the change from sulphate to nitrate, (2) 130 grams for changes in the sphere structure and (3) 5 grams for the tamper change and the four chamber monitor holes to be used in the new set up.

The actual critical mass would have been 773 grams had there been enough material with 14.6 per cent enrichment. The estimates above are seen to be quite accurate and indicate that the separate measurements were additive.

The original prediction was not this close due to the uncertainty existing at that time in the absolute calibration of lopo. This lead to an underestimate by a factor of two in the effect of the change from sulphate to nitrate.

The available 14.6 per cent material amounted to 767 grams, or, not quite enough to go critical. An additional 102 grams of U^{235} then procured had a 10.8 per cent enrichment so that after mixing a concentration of 14 per cent resulted which went critical with 806 grams. Recently, due to the loss of some of the original material and the need for more reactivity 44 grams of 42 per cent material was added. The present concentration is 885 grams of 14.5 per cent U^{235}.

4.3-2 Constructural Details

The major components of the high power water boiler, which will be described in the following sections are the following:

The reactor (1) (see Figure 25) is a 12 inch diameter stainless steel sphere containing the active solution. It is surrounded by a tamper or reflector consisting of a core of BeO bricks (2) supplemented by a shell of graphite (3).

Accessories to the reactor are the cooling coil (4) and the pipes for the flushing air and level indicators (not shown in Figure 19 . The sphere is pierced by a horizontal pipe ("glory hole") (5) to enable one to have access to the highest possible neutron flux. Between the tamper and the thermal column (6) is a bismuth wall (7) which provided gamma ray protection for the thermal column. A removable cadmium curtain (8) can be used as a shutter for thermal neutrons in the column. The shield around the entire assembly consists of 4 inches of lead (9), 1/32 inch of cadmium and 5 feet of concrete (10).

(1) Sphere assembly (1/16 inch wall 18-8 type 347 stainless steel throughout all joints exposed to solution or vapor have stainless steel welds)

(a) Sphere - A one foot diameter stainless steel sphere contains the active solution. The wall thickness varies from 1/16 inch at the poles to 3/64 inch at the equator. The sphere consists of two spun hemispheres with a 1½ inch ID tube welded into the top and a 3/4 inch tube into the lower hemisphere. A 1 inch pipe is welded horizontally thru the sphere to permit irradiation at the highest possible flux. The pipe is slightly off center in order not to pass through the weld joining the hemispheres. This weld, the last to be done in the assembly, was made by flowing the narrow flared lips on the two hemispheres together with an acetylene torch. A helium atmosphere was maintained inside the sphere to prevent oxidation (4) Figure 21 shows details of the sphere assembly.

(b) Cooling coil - A six turn cooling coil ½ inch ID and an effective length of 157 inches is wound in the form of a helix. Figures 21, 22 show the appearance of the coil. Calculations for natural convective cooling indicated that 50 cubic centimeters per second

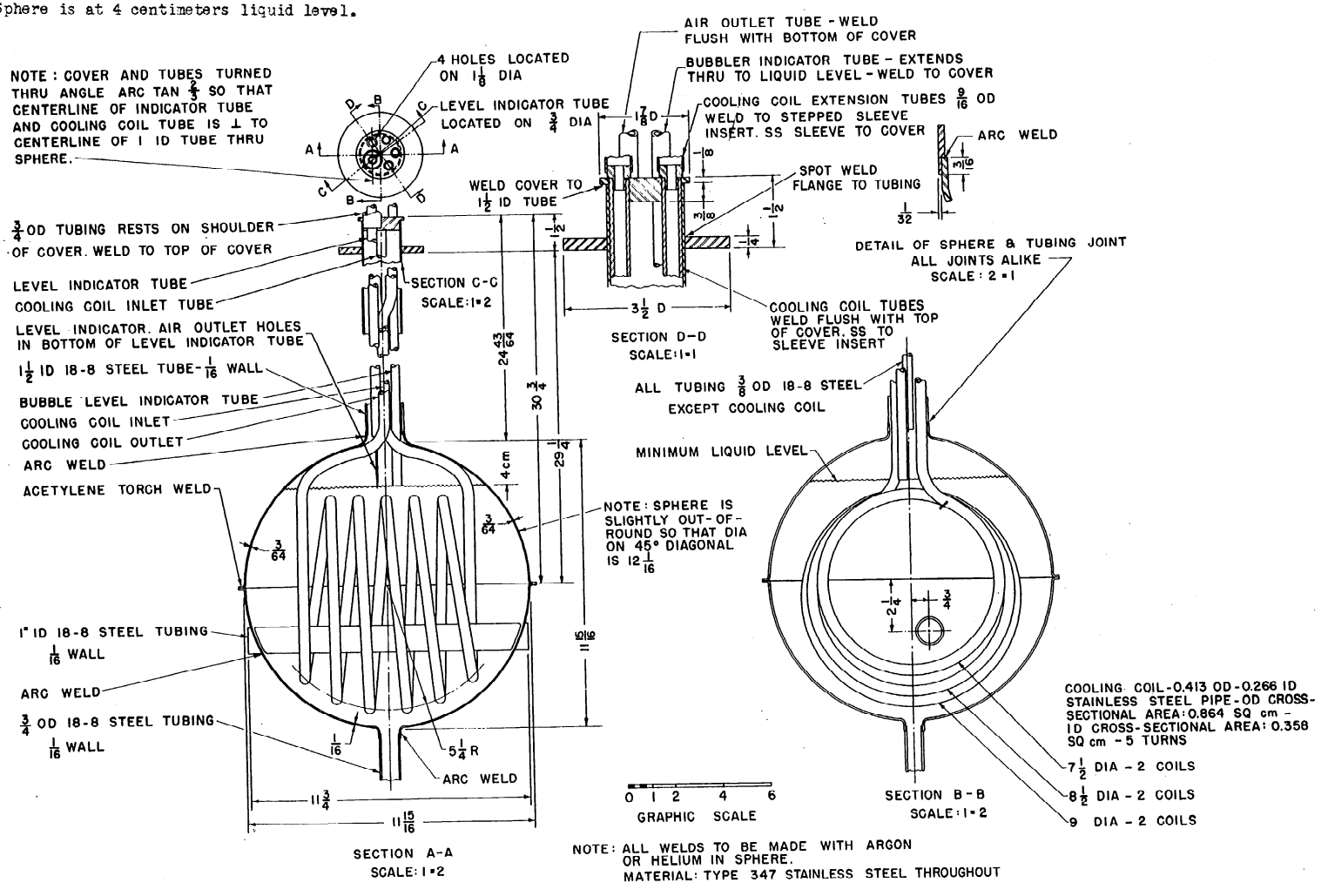
Figure 21

Hypo Sphere Assembly

Total Volume of Sphere	14700	cubic	centimeters
Volume of 3/4 pipe	200	"	"
Total	14900	"	"
Unused Volume of Sphere	700	"	"
Coil Displacement Volume	343	"	"
1 inch Tube Displacement Volume	180	"	"
Total	1223	"	"

Minimum Volume Solution Required 13780 cubic centimeters

Note: Unused Volume of Sphere is at 4 centimeters liquid level.



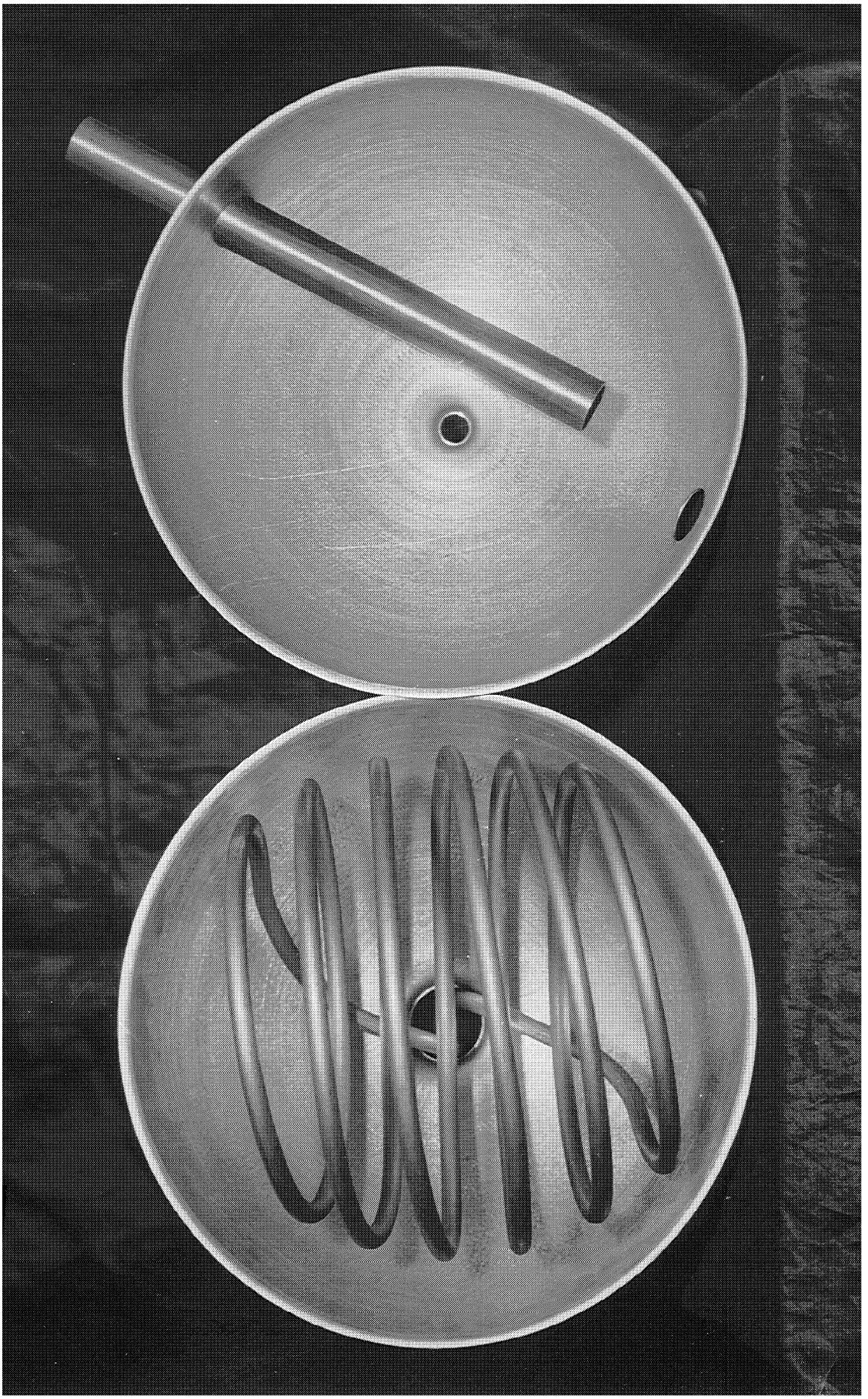


Figure 22

Cooling Coil

of water through a 72 inch length of such a tube should give adequate cooling for operation at 1 kilowatt with an approximate rise of 30 degrees C above room temperature cooling water. Electrolysis of the water in the solution was expected to produce 2 cubic centimeters per second of hydrogen and oxygen due to the heavy ionizing currents in the sphere. Tests indicated that the cooling efficiency of a coil might be cut in half by bubble formation throughout a mock solution. The cooling tube was overdesigned to take care of this possibility. The inlet outlet water pipes are arranged so that the coil will drain by gravity. A water bucket in the outlet serves as an indicator to show that water is flowing at 50 cubic centimeters per second and also turns the water cooling units on. These units lower the inlet water temperature at 5 degrees C and permit 6 kilowatt operation the year around. The water outlet flows through a tank with several compartments before leaving the shield. This permits the short lived radioactivity of the water to die out before the water gets to the outlet about 75 feet from the building. See Figure 23 for cooling water layout.

(c) Flushing air and level indicator - Due to the explosive nature of the gas released by electrolysis and the highly concentrated radioactive gases produced in the solution means of diluting and flushing out these gases was required. Approximately 30 cubic centimeters per second of air is admitted through a 3/8 inch ID tube which is pointed at the end and serves as a solution level indicator as well as air inlet. The tube is 11 feet long and is held concentric to a 3/4 inch tube by means of a single lavite insulator 7 feet from the sphere. It can be raised or lowered by a selsyn controlled gear; a syphon forms the flexible gas

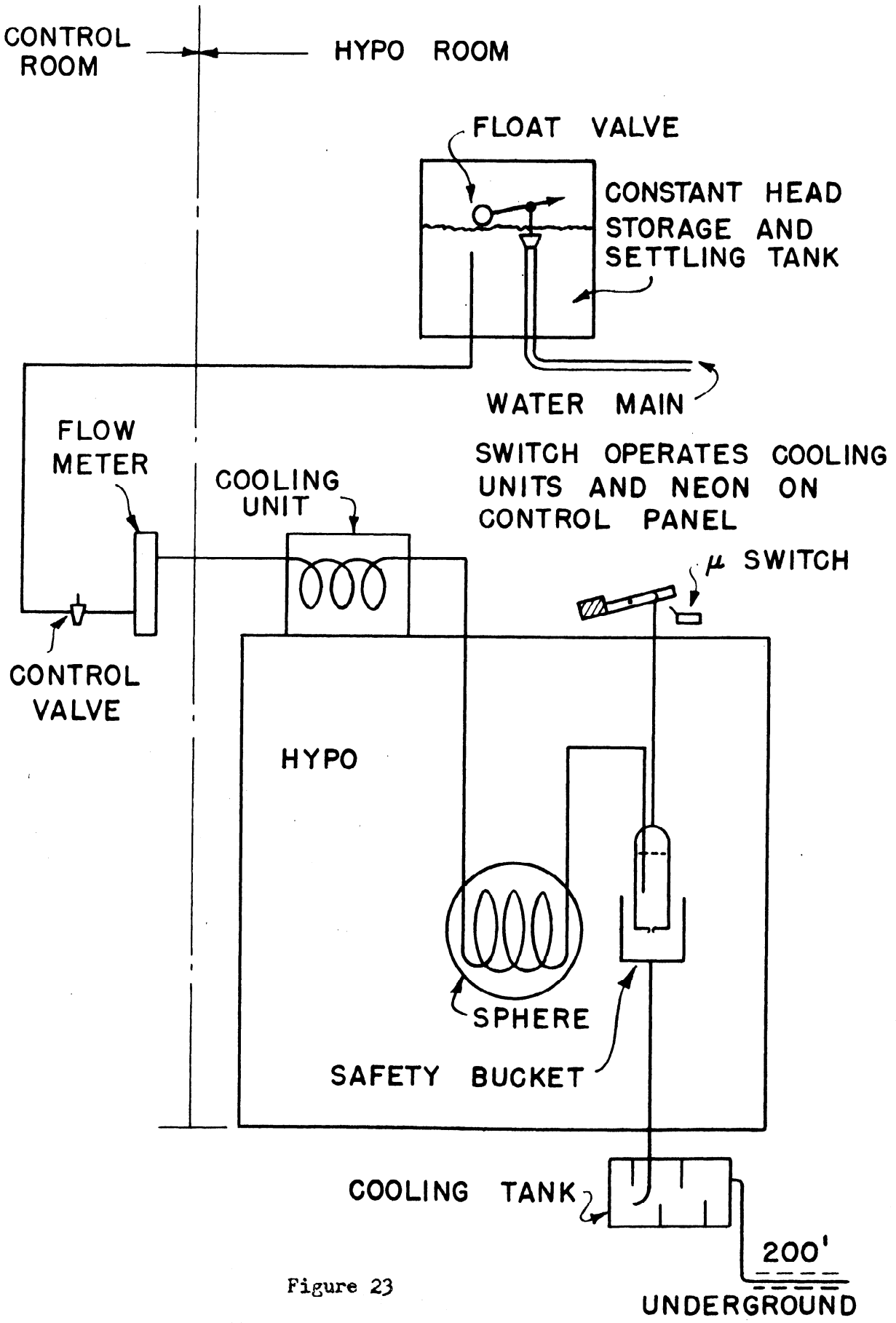


Figure 23

Water Cooling System

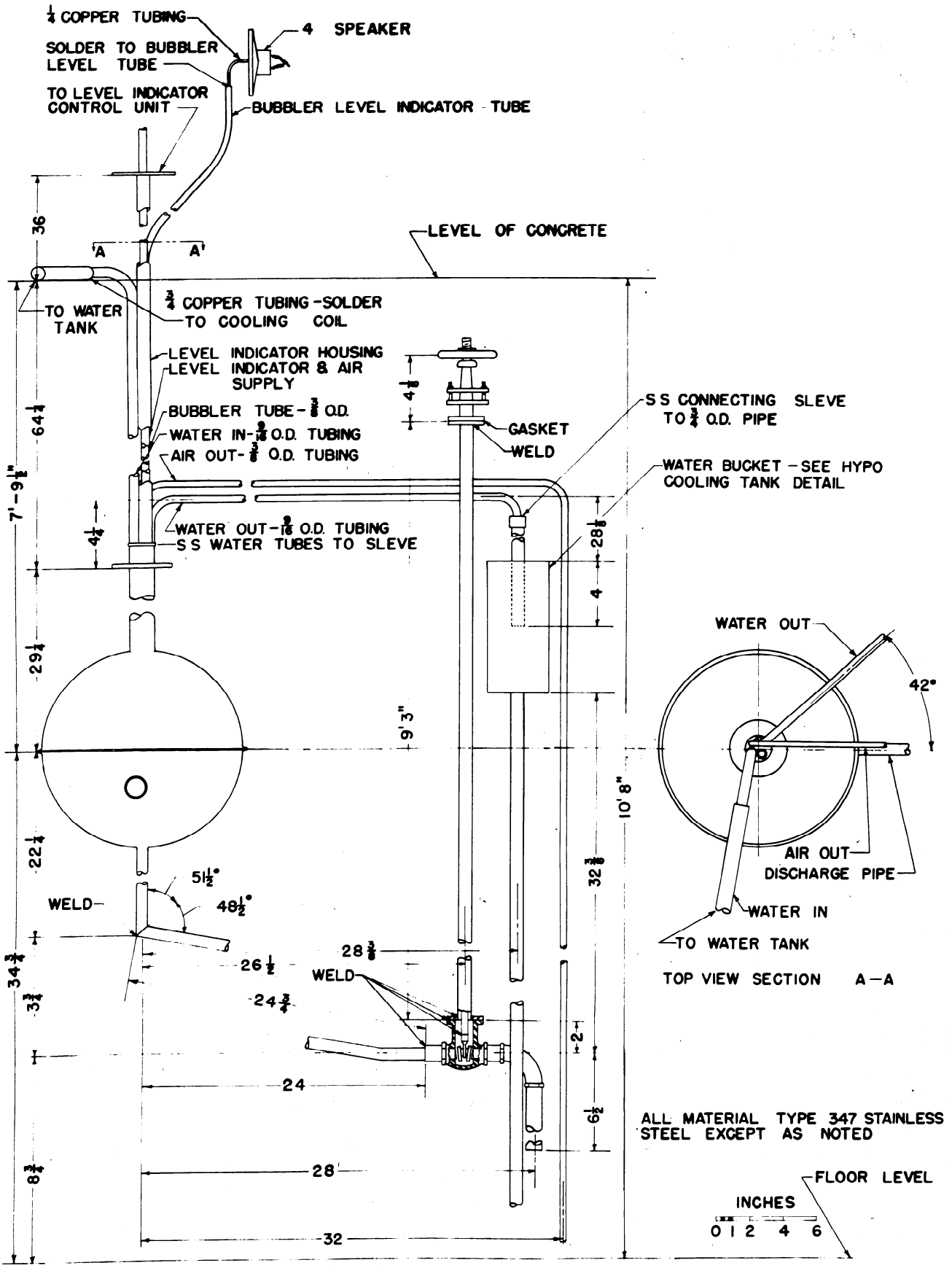


Figure 24

Hypo Sphere Assembly

seal. A revolution counter gives the pointer position, while a neon light, requiring a fraction of a microampere, in conjunction with an electronic circuit indicates the liquid contact. The level can be read to .01 inches. These concentric tubes have been used for a rapid analysis of the boiler gas by making the outer tube the air inlet and the central one the gas outlet leading directly to the test equipment.

(d) Bubbler level indicator - A 3/8 inch tube extends 4 centimeters down into the sphere and acts as a minimum solution level indicator. If the tube is in the solution, the pressure changes produced by a small air flow through the tube is amplified and can be made audible or visible at the control panel by means of a loud speaker and neon light. To permit an easy escape for the bubbles and prevent possible frothing from electrolysis as well as to allow adequate space for the expansion of the solution, the sphere is not completely filled. A maximum solution level of 3 centimeters from the top and a minimum of 4 centimeters from the top are used.

(e) Temperature indicator - A copper constantin thermocouple in a 3/16 inch tube extends through the bubbler tube into the center of the sphere. Thermocouples are connected also to inlet and outlet water. These temperatures are read directly on a panel meter. Couples at various tamper points were found unnecessary for the power used.

(f) Air outlet - A 3/8 inch air outlet tube is welded into the top of the $1\frac{1}{2}$ inch upper sphere tube. This is connected to a small chamber outside the boiler shield which acts as a safety solution catcher. The presence of liquid in the air outlet line is shown by a contactor and panel light. Some platinum gauze in an en-

larged section of the tube acts as an explosion stop in case the flushing air flow should stop and one of the contactors cause a detonation. Beyond the safety catcher the air goes 200 feet under ground to large silica gel drying tanks which can be reactivated by remote control. From the drier a 200 foot copper tube extends underground and then an 1800 foot saran tube takes the highly active gases a sufficient distance from the building to reduce the radiation there to less than .01 R per 8 hour. The saran tube is strung between trees and fastened about 15 feet above the ground. This simple expedient was possible due to the isolated location of the building. A considerable portion of the fission activity is carried out by the flushing air (about 15 R per hour a few feet from the line while operating at full power). Numerous signs have therefore been placed along the line to warn people to stay at a safe distance.

(g) Drain tube and dump valve - The original arrangement for dumping solution to the chemists decontamination equipment by means of a remotely controlled valve, is shown in Figure 23. Due to the formation of a precipitate after 1000 kilowatt hours of operation the lower 3/4 inch tube and valve became plugged and could not be used for draining the solution.

Since the exact cause of the precipitate was not known at that time, it was thought advisable to reduce any dead space where incomplete mixing might cause further precipitation. For this reason the lower 3/4 inch pipe and drain valve were removed. A long 1/8 inch stainless steel tube was installed to replace the 3/4 inch tube. This tube runs horizontally from the bottom of the sphere to the back of the tamper and is then brought verti-

cally up through the shield. The acid and water addition are now made by means of this tube and air can be bubbled through to insure better mixing. This latter procedure has not been found necessary, however.

(2) Tamper, Thermal Column and Radiation Shield.

(a) Tamper - The tamper, or reflector, consists of a 24 inch x 24 inch x 27 inch BeO core next to the sphere, surrounded by graphite to form a 60 inch x 48 inch x 60 inch rectangular parallelopiped, (Figure 25). The BeO blocks are those described above under lopo, the graphite consists of 4, 2, and 1 foot long stringers 4¼ inch square. The BeO and graphite have experimentally determined densities of 2.69 and 1.614 and diffusion lengths of 48.45 centimeters and 29.4 centimeters respectively.(38)

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(38) J. Hinton, L. D. P. King: Exp. Determination of Diffusion Length of C Neutrons in BeO, LA-160.

Two safety drip pans were installed in the tamper to prevent loss of solution in case a leak should develop (Figure 26 and 27). A .020 inch stainless steel pan was placed betweem the BeO and graphite and a large 3/16 inch lead pan is placed beneath the entire tamper. Both drip pans drain into a funnel leading to the chemists vault.

The tamper is designed to permit the removal of various blocks of graphite in order to obtain neutron beams, irradiate samples, insert monitors, etc. The horizontal ports are shown in Figure 28. Two of these ports extend through the graphite up to the BeO. The third is specifically shaped to extend up to the sphere and is drilled with a 1 inch diameter hole coaxial with the 'glory hole' through the sphere. Vertical parts are shown in

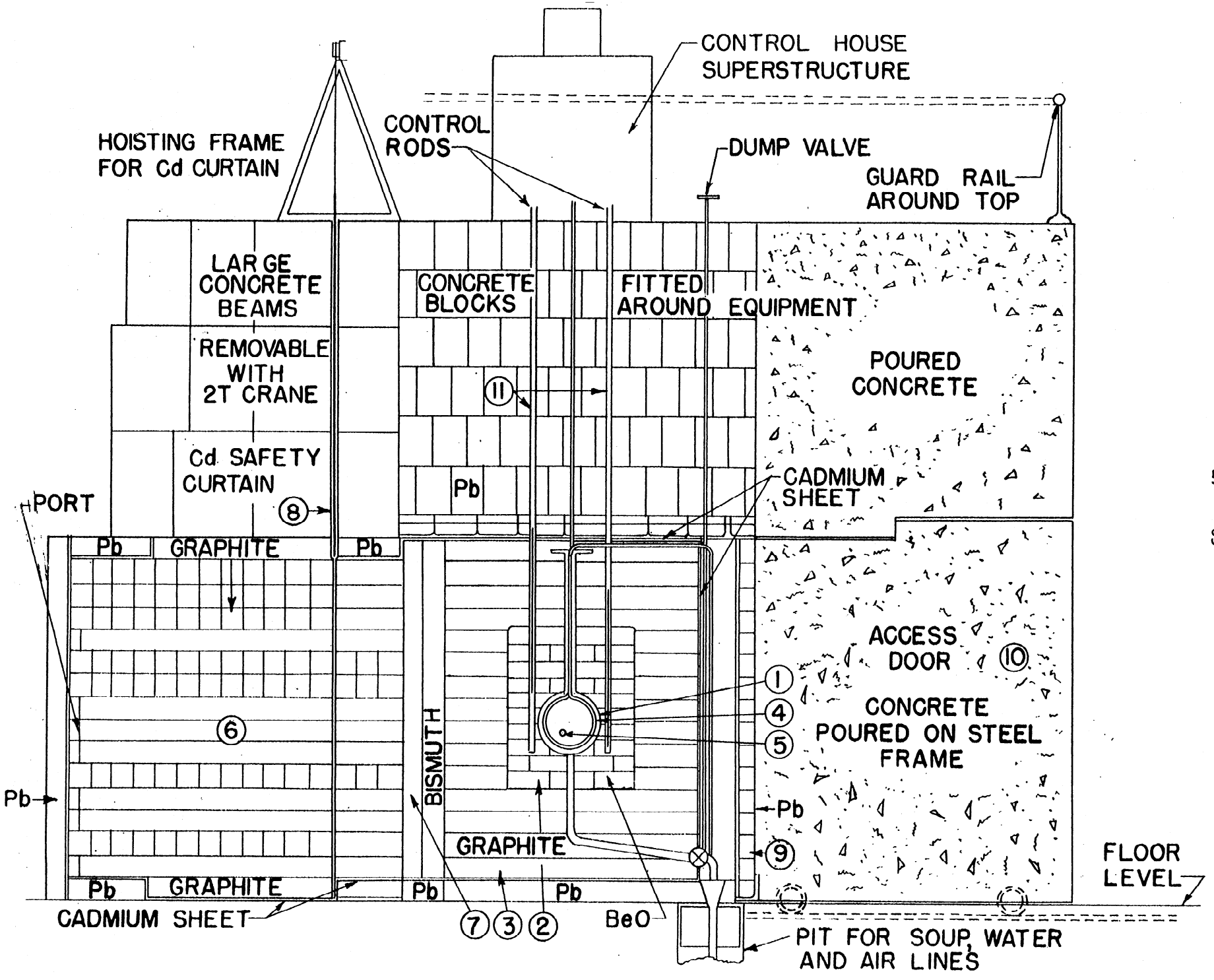


Figure 25

Section through Hypo (simplified).

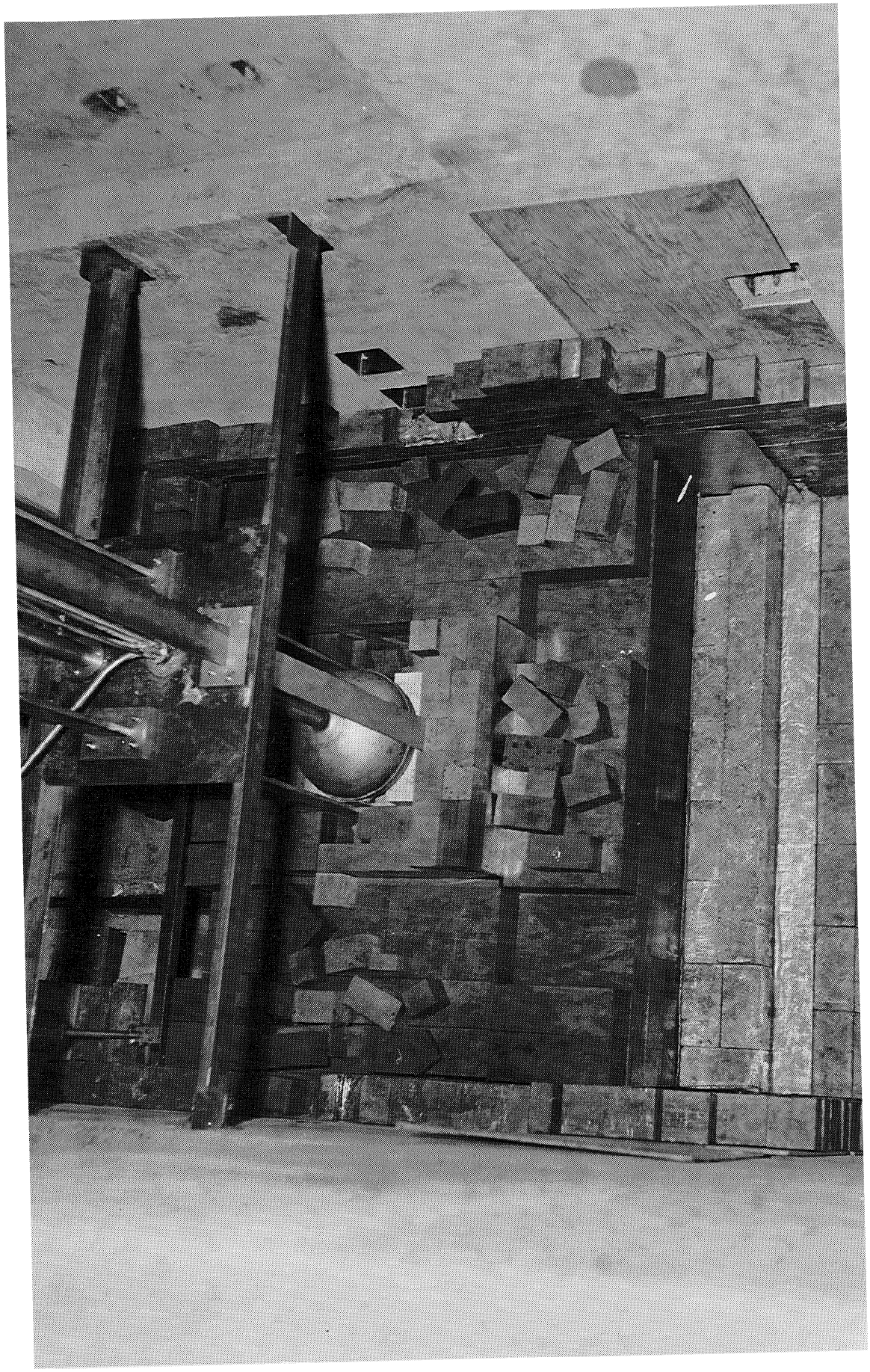


Figure 26

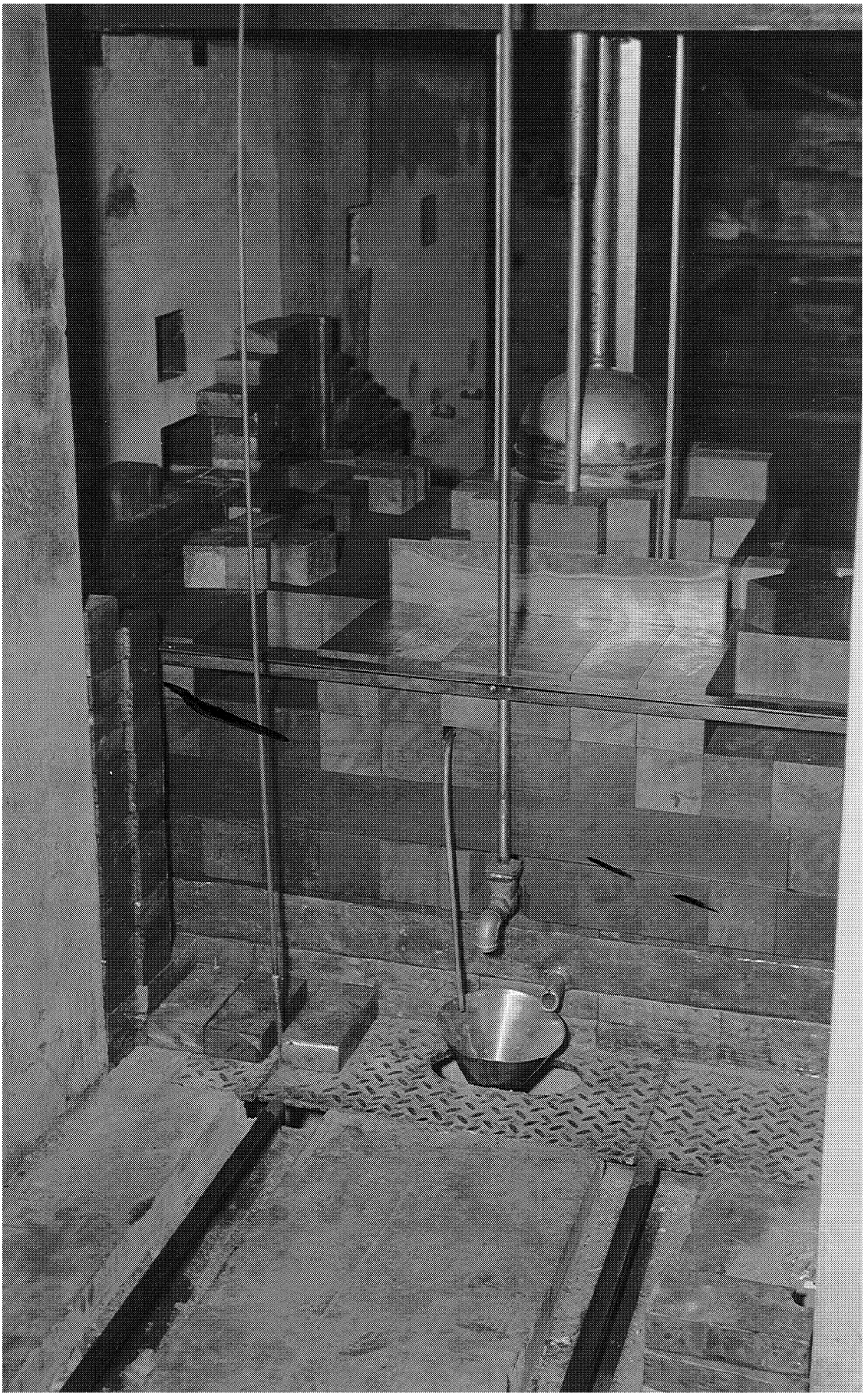
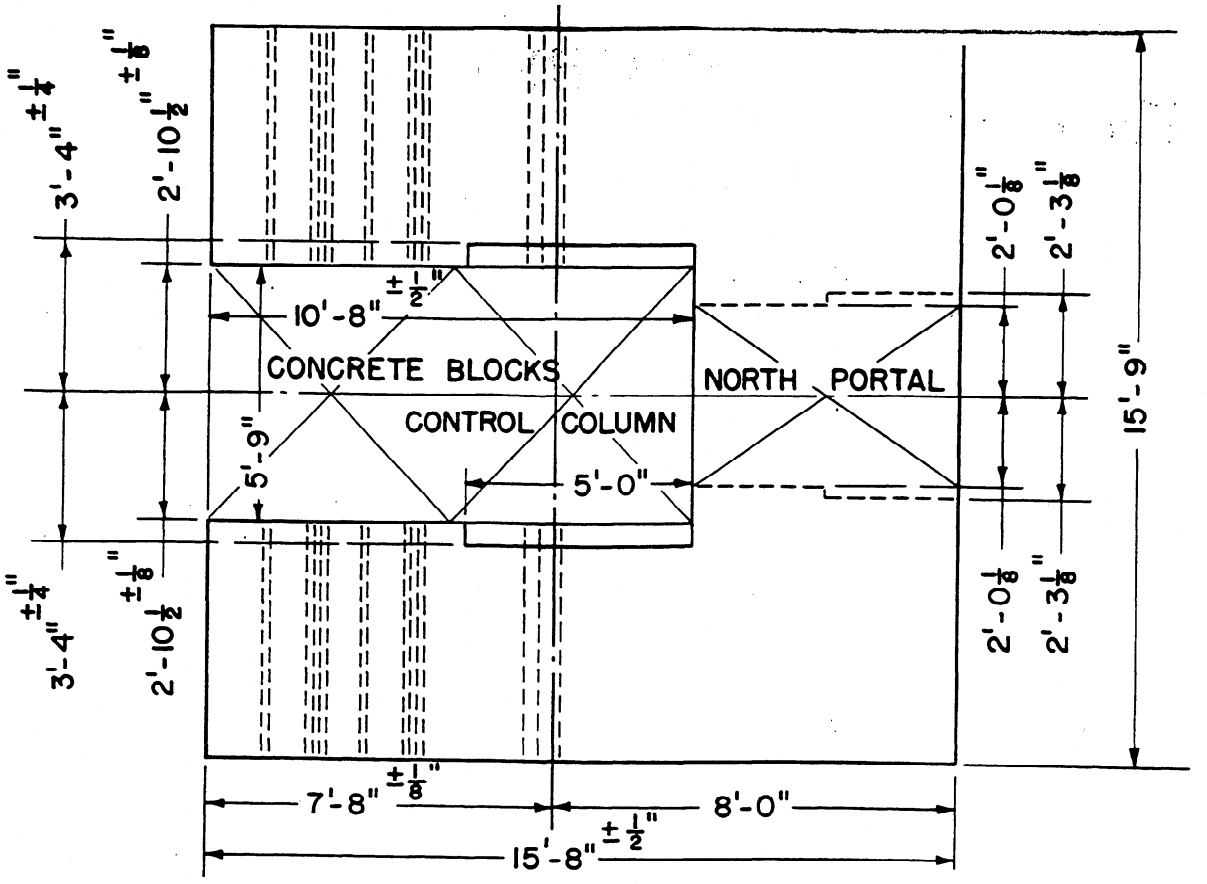


Figure 27



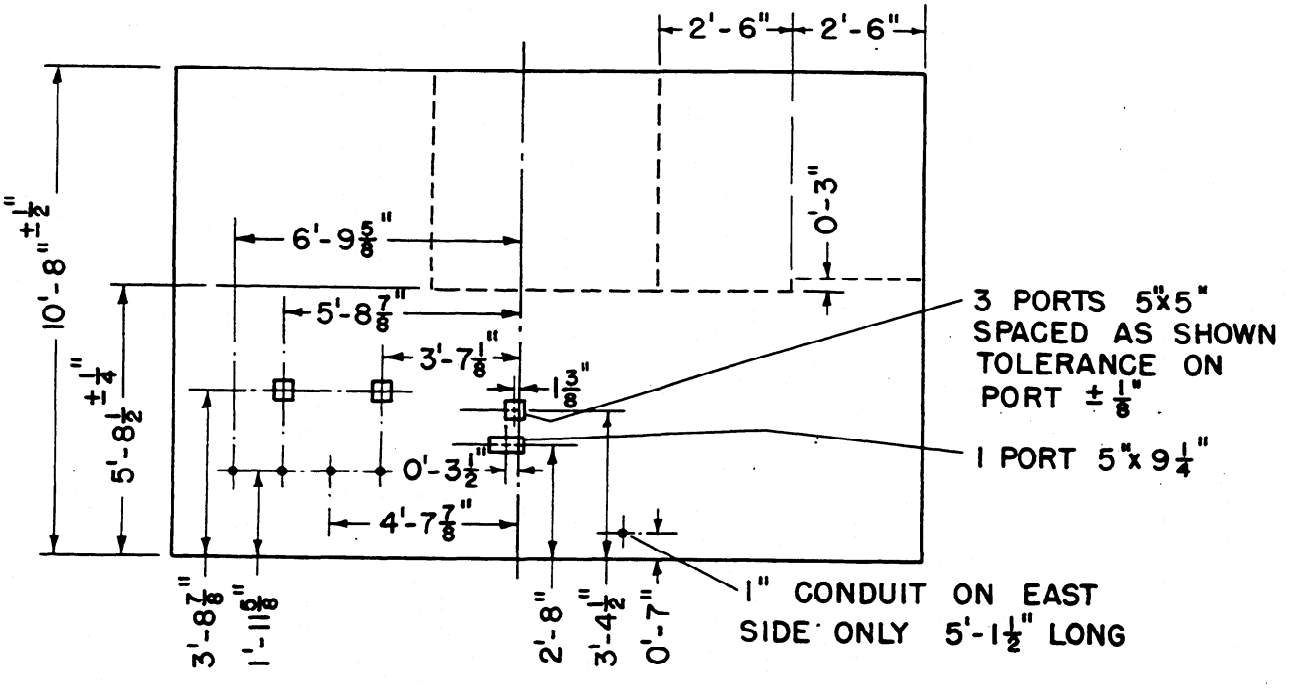


Figure 28

Ports in Shield

Figure 29. These have been primarily used for monitors.

(b) Thermal column - Adjacent to one side of the tamper is a 5 foot cube of graphite to thermalize the neutrons. Numerous experimental ports have been provided here as in the tamper (Figure 28). The transverse ports can be made to extend completely through the column. The longitudinal ports can be varied almost at will but normally extend to the cadmium curtain. The largest port obtainable without complete remodeling of the thermal column is 34 inch x 34 inch extending into the thermal column 4 feet. A cadmium curtain extends across the thermal column 4 feet from the front of the column. This curtain can be raised or lowered by an electric motor with gear reduction and pully system controlled either from the control room or from the end of the column. The curtain acts as a shutter for thermal neutrons and can be used for timing purposes or to reduce the neutron intensity during changes in experimental equipment.

(c) Radiation shield - In order to provide adequate physiological protection and to reduce the neutron and γ-ray backgrounds to sufficiently low levels for experimental purposes an effective radiation shield is essential. This is accomplished by a combination of cadmium, lead, concrete, and bismuth.
All surfaces of the tamper and thermal column are covered with 1/32 inch of cadmium to stop the thermal neutrons. The cadmium is backed by at least 4 inches of lead to reduce the resulting γ rays. The entire unit is then enclosed by 5 feet of concrete (except at the end of the thermal column) to reduce the remaining γ rays and fast neutron leakage. The concrete is all poured except for that above the tamper and thermal column (Figure 28).

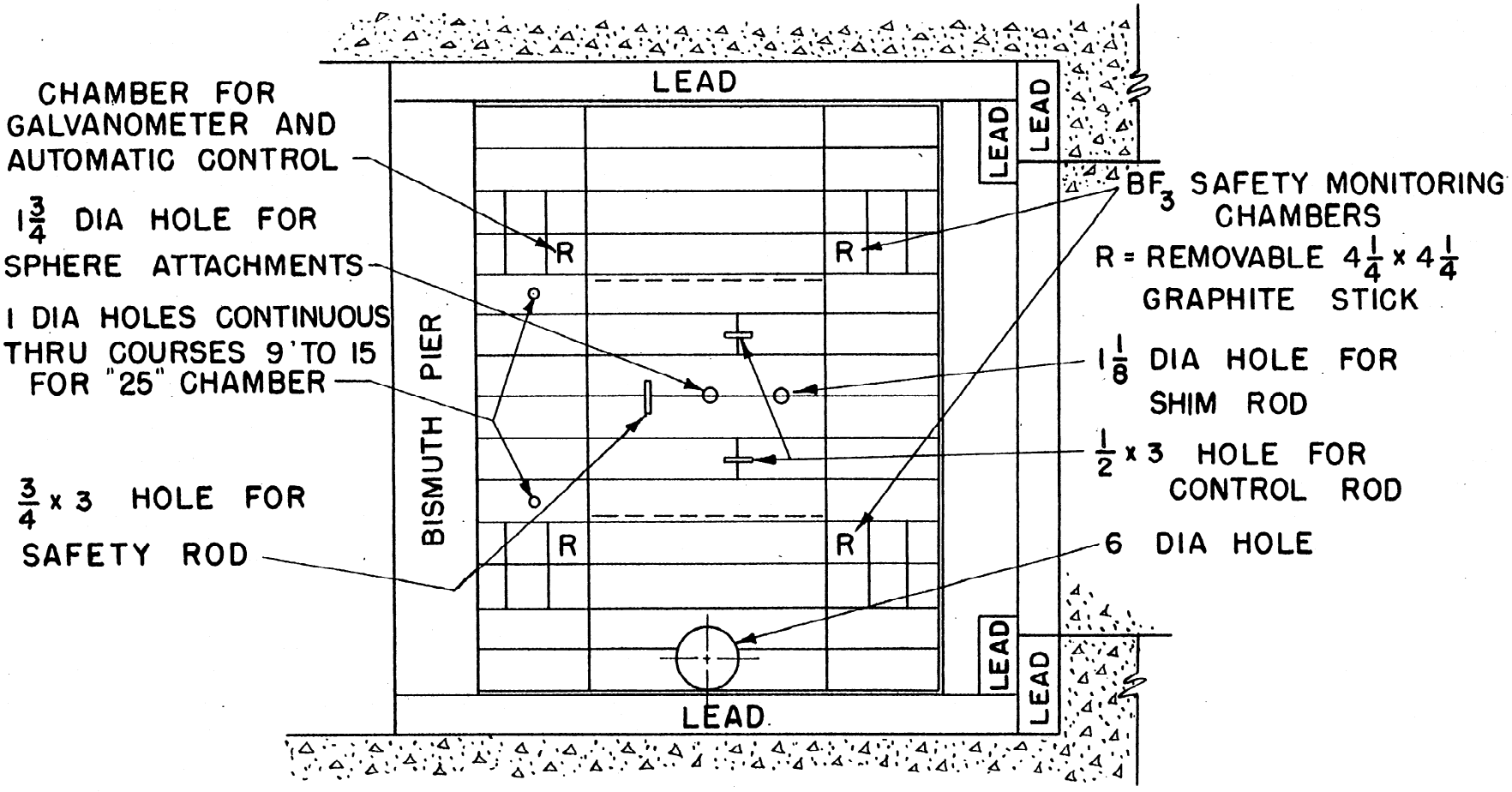


Figure 29

Top-view of Tamper.

The concrete at the back of the tamper was poured on a cart set on rails to permit easy access to the tamper. The shield on top of the thermal column is in the form of large cement blocks supported by the column. Above the tamper the shield is supported by beams resting on a ledge provided by the concrete side walls. This portion of the shield was originally made with a very low strength cement mix and small concrete blocks. Later, this was replaced by building bricks and sand. Both types of construction have been satisfactory and can be removed without much difficulty if access to the sphere is necessary from above.

To give additional γ ray protection in front of the thermal column (where there is only graphite if work is being done on the column) an 8 inch thick pier of bismuth is placed between the tamper and the thermal column. This results in a substantial decrease in the direct γ radiation from the sphere itself, without a serious neutron loss. To make up for the lack of concrete in front of the thermal column the neutron and γ ray leakage is further reduced by adding a 1 inch layer of polythene and a 3/4 inch layer of boron plastic inside the cadmium and increasing the thickness of the lead to 8 inches. The G. M. counter background in front of the column when operating at full power is only twice that due to cosmic rays.

All of the parts which extend through the concrete are normally plugged with wood capped by cadmium and 2 inches of lead. The parts opposite the sphere are shielded by wooden plugs and 4 inch lead doors to permit easy access to the "glory hole". Figures 30 and 31 are side and front views of the shield.

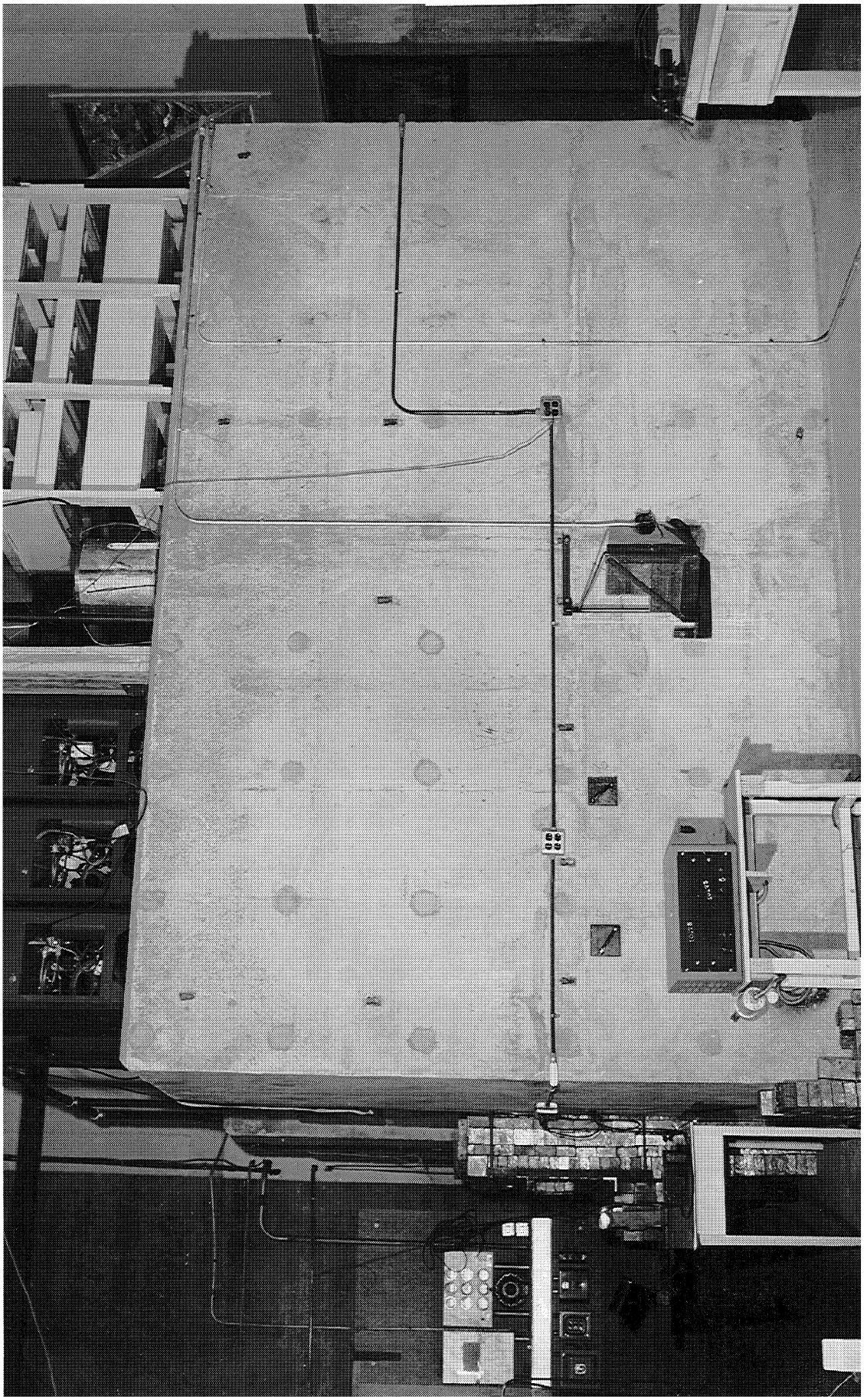


Figure 30

View of Shield

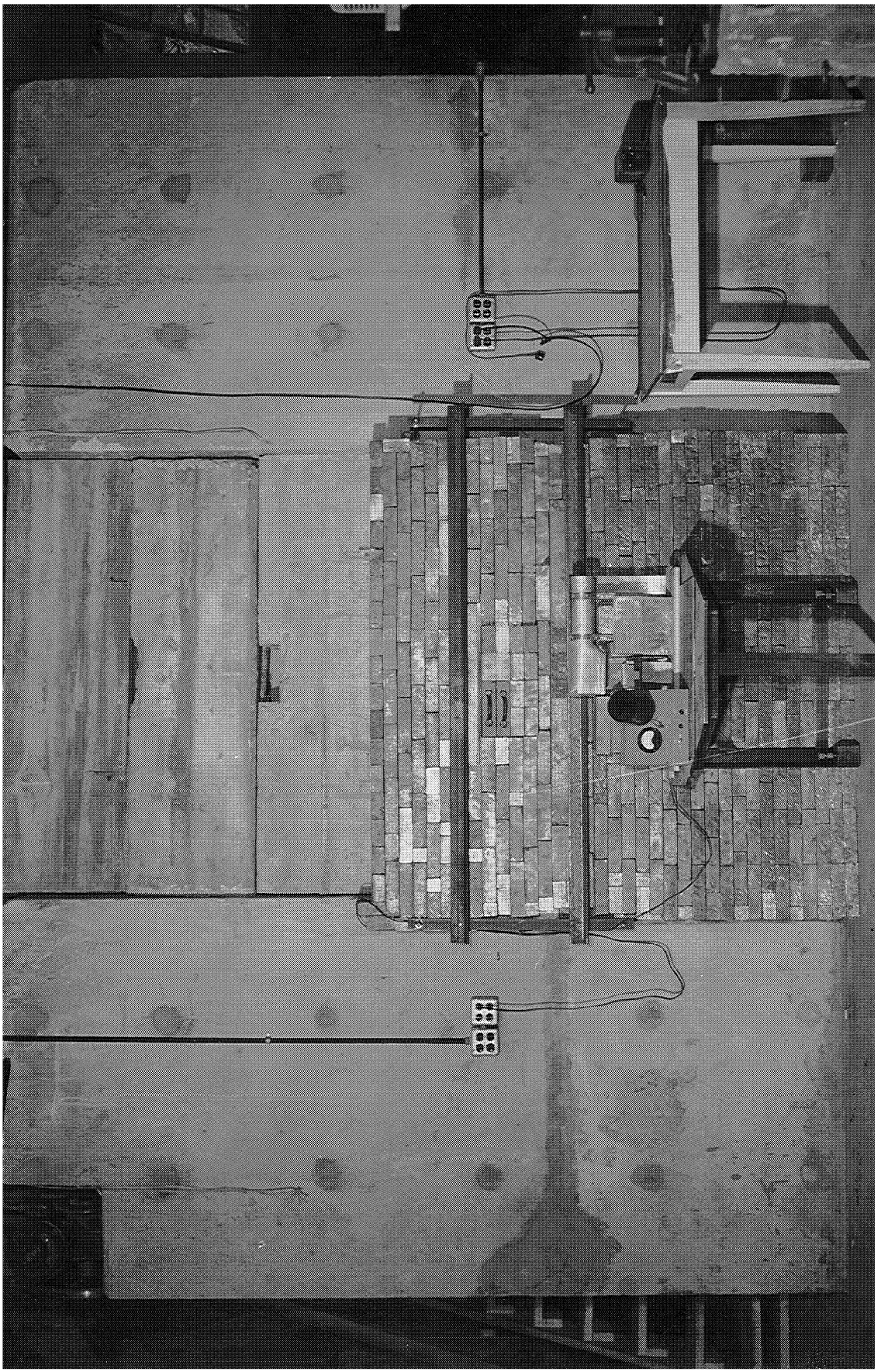


Figure 31

View of Shield

(3) Control, shim and safety rods.

The reactivity of the boiler is controlled by means of four cadmium rods operated from the control room; two control rods, a shim rod, and a safety rod. The latter always remains out during operation. It is used only to stop the chain reaction in case the intensity should get too high. For additional safety the two control rods are designed with a release mechanism so that they can be used for safety as well as control. These safety devices are necessary in case the power is raised too rapidly. Under normal operating conditions the boiler is self-regulating due to the temperature effect; however, if the rods are pulled out too fast, without a safety device the heat liberated might be enough to vaporize the solution before the increased temperature had time to control the reactivity. The fastest period theoretically obtainable with the boiler is approximately .02 seconds. The rods are mounted vertically so that those used for safety may fall freely when released. This eliminates the necessity of a fast mechanical device to push them in.

The total equivalence in grams of U^{235} of the control and shim rods is about 160 grams which is about 35 grams more than that necessary to compensate for the maximum temperature effect. The arrangement of the four rods in shown top view in Figure 29. Cadmium is contained in the lower 30 inches of the rod. The rods extend from the top of the cement structure to 5 inches below the bottom of the sphere. They have a total motion of 2 feet, which means that when they are out, the bottom of the cadmium is about at the top of the BeO tamper.

Control rods: The control and safety rods slide in metal sheath:

as shown to scale in Figure 32. For minimum neutron absorption the lower halves of the sheaths are made of 1/32 inch wall aluminum. Both halves of the three sheaths can be seen in place in Figure 21; above the iron plate the sheaths are iron.

The two control rods are identical. They were made as light as possible so that they could be operated directly by selsyns. Each rod is 113 inches long and weighs 4 pounds. It consists (Figure 32) of two long strips of dural 2 inches apart. The lower end of the gap between the strips is filled by a sheet of Cadmium (30 inches long, 2½ inches wide and .032 inch thick) sandwiched between two similar sheets of dural. As shown in cross-section in the figure, each side of the cadmium sandwich fits in a slot cut in the corresponding dural strip. To minimize the total weight of the rods this slot extends the full length of each strip.

Rack and pinion devices are used to move the rods. The racks are 26 inches long mounted at the top of each rod between the dural strips. The pinion gear is mounted directly on the selsyn shaft.

In order that the rod act fast enough for safety, it must be allowed to drop freely. Since it must also have a fairly accurate position control a rather complicated mechanism is necessary. This is shown in Figures 33 and 34.

To allow the rod to drop freely the pinion gear (1), Figure 33, must be released from the selsyn. For this reason the pinion is coupled to the selsyn. In order to drop the rod the coupling (2) is broken and the pinion rotates freely on the selsyn shaft. The coupling is held closed against the force of two springs by a push

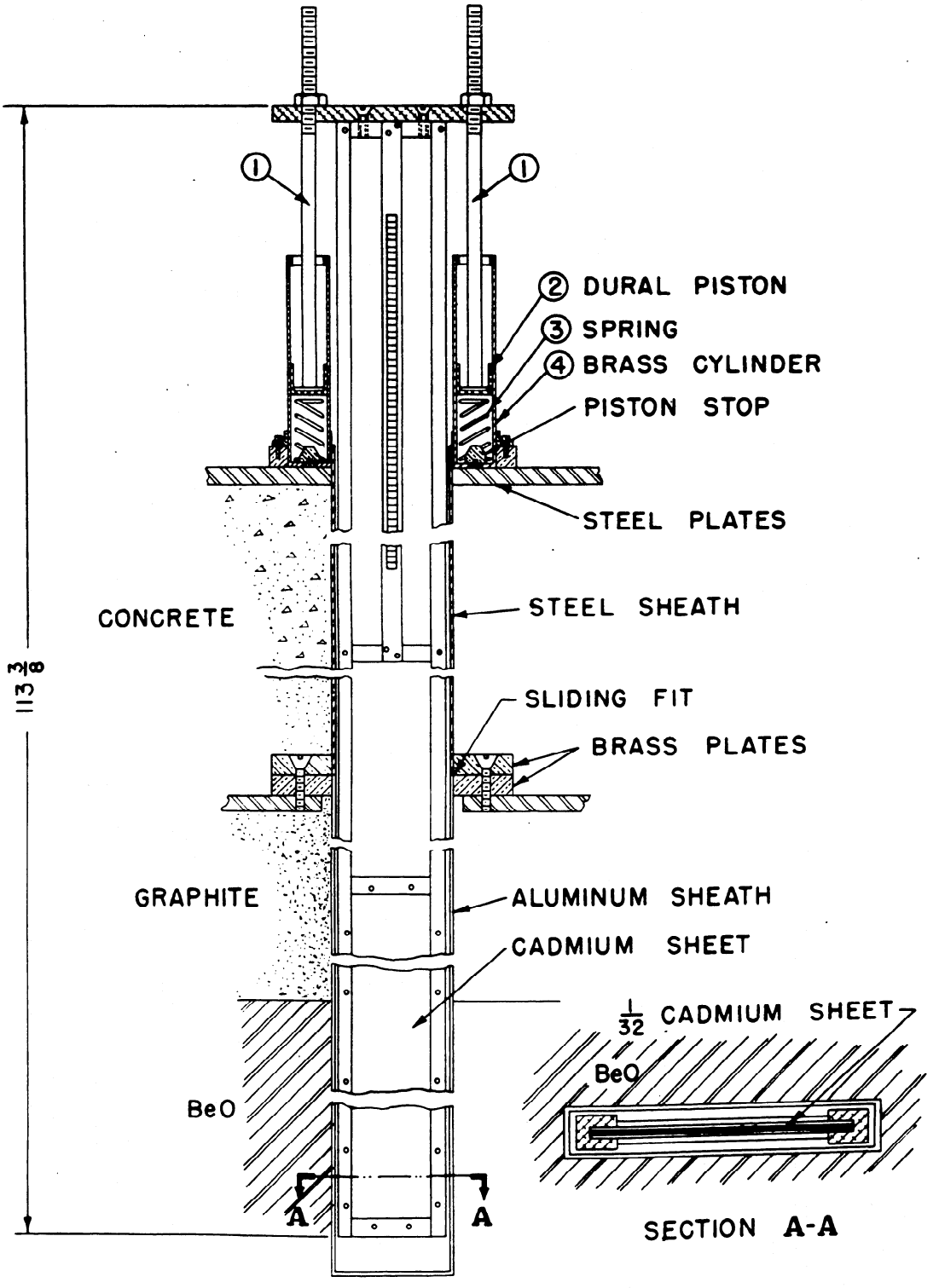


Figure 32

Control rod Assembly

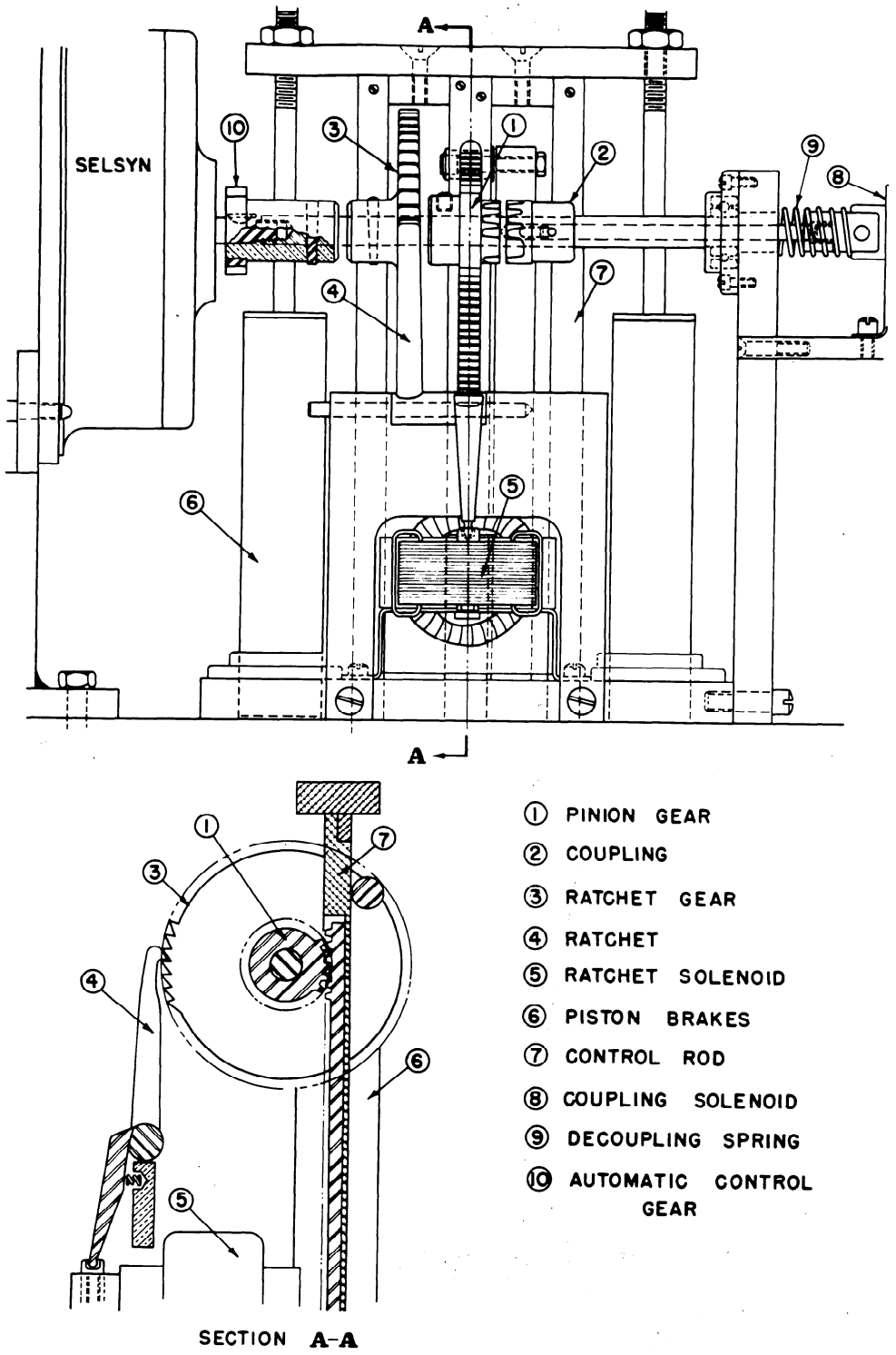


Figure 33

Control rod driving mechanism

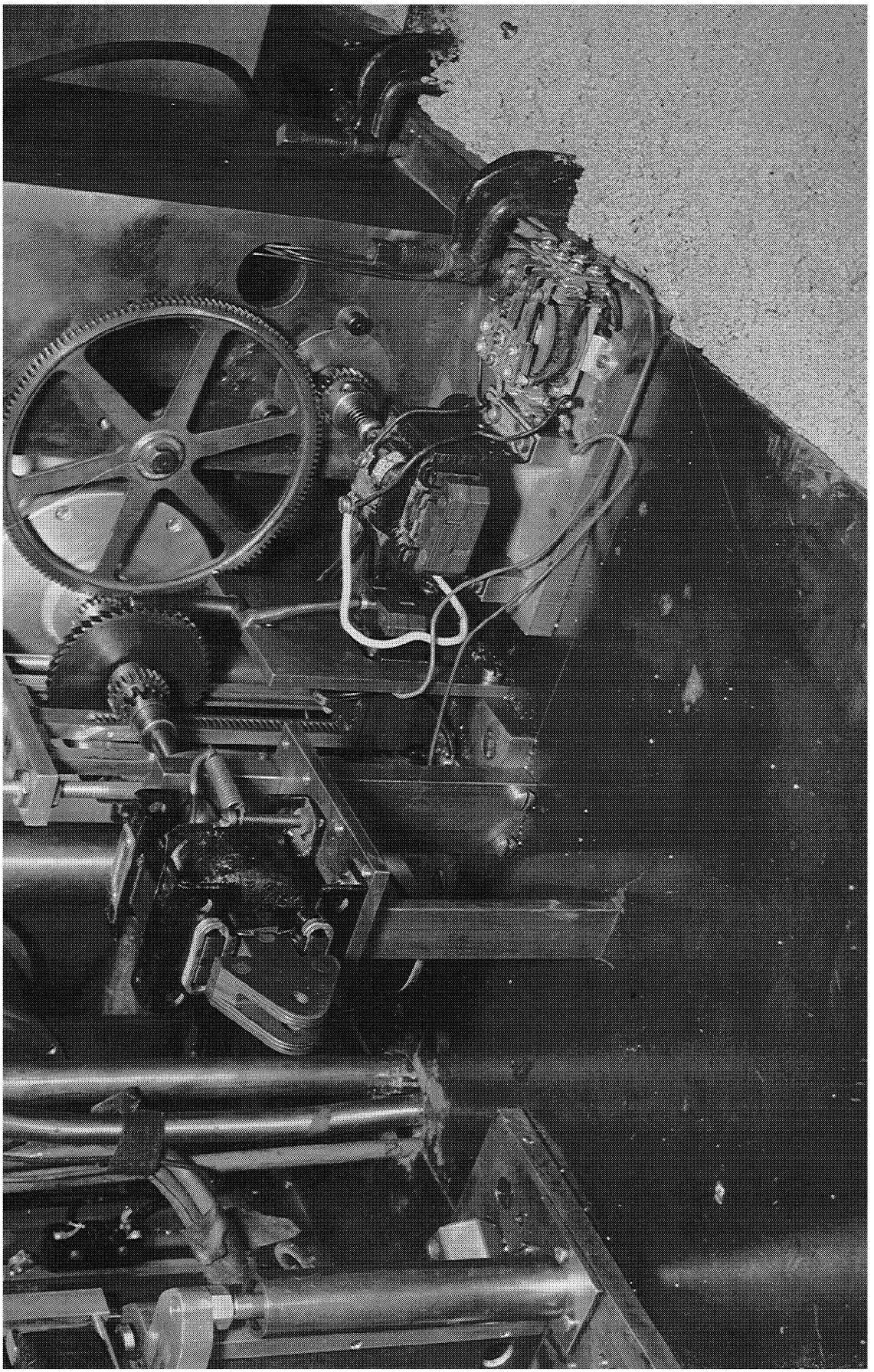


Figure 34

Control rod driving mechanism

A. C. solenoid (8). When the current through the solenoid is cut off, the springs open the coupling and the rod drops in. With this arrangement the rods will automatically drop, in case of power failure.

It was originally planned to use the old control rod from lopo for fine adjustment between predetermined fairly large intervals of the new rods. In order to make these rods more useful the stationary intervals were reduced to a 1/16 inch in the final design with continuous motion between intervals possible for control purposes. The rods are held at any desired interval by means of a ratchet (4) which engages in a tooth of a ratchet gear (3) fastened to the selsyn shaft. The gear has 48 teeth since one revolution of the pinion moves the rod 3 inches, the rod moves 1/16 inch per tooth. The ratchet is engaged or disengaged by a solenoid (5). If disengaged the rods can be moved by turning the knob fastened to the shaft of the selsyn in the control room (Figure 35). In this way the operator actually feels the weight of the rod. The selsyns used are Navy #7G. They are rated for 3.4 inch ounces per degree, linear to 30 degree of phase lag. Since the radius of the pinion is $\frac{1}{2}$ inch and the rods weigh 4 pounds each, the control-room-selsyn leads the hypo selsyn by 10 degrees, or 1-1/3 notches on the ratchet. The position of the rods is indicated by a revolution counter geared to the control room selsyn shaft as shown in Figure 35. Each number in the first digit represents one notch on the ratchet or 1/16 inch motion of the rod. When the rod is all the way out the indicator reads 350, i. e., 7.3 turns of the selsyn.

During operation of the boiler the new rods rather than the old

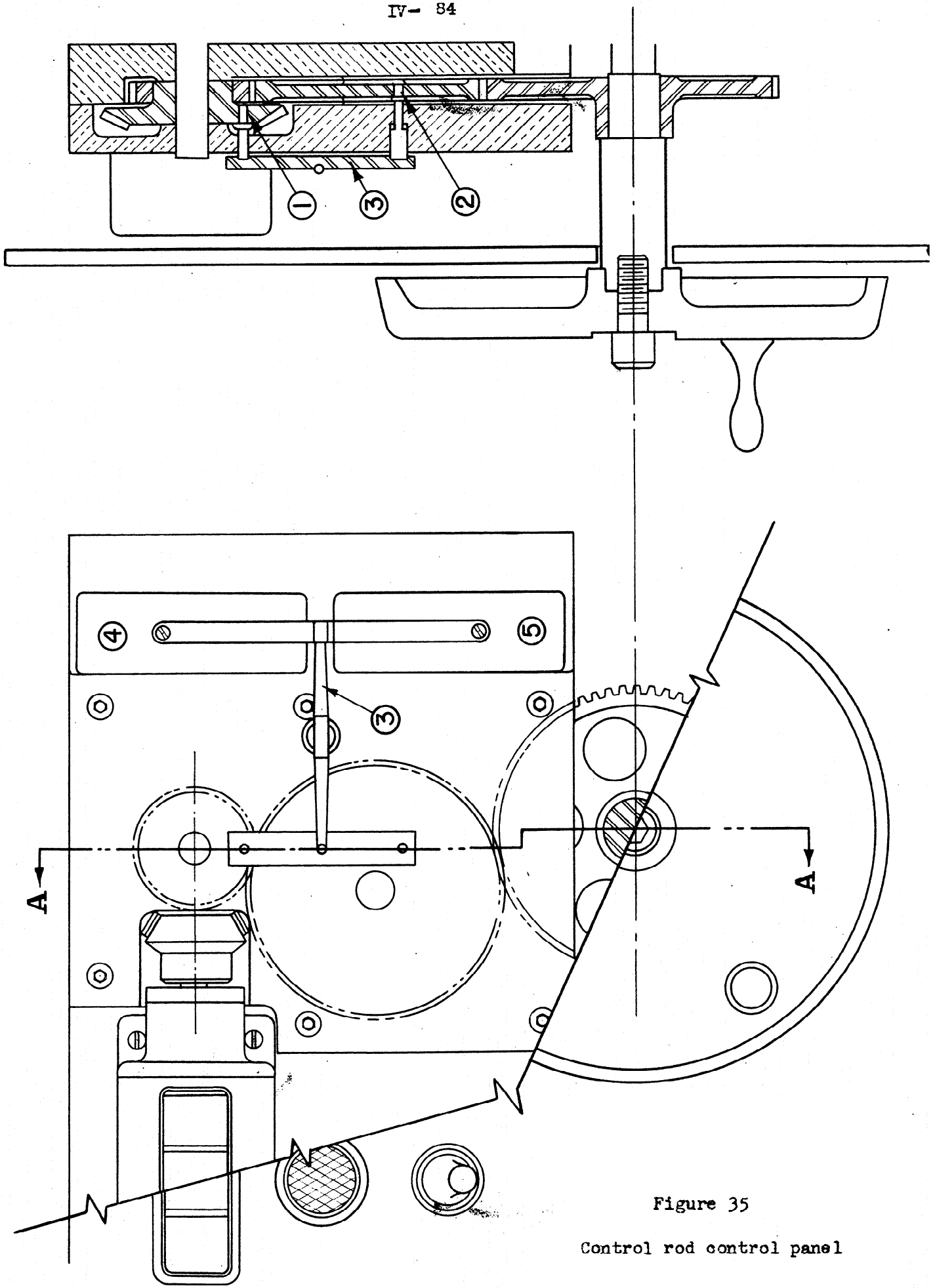


Figure 35

Control rod control panel

control rod have been found to be the most convenient control. This latter rod is therefore called a shim rod. One rod is usually left out in some fixed position. The other can be used for either manual or automatic control.

The circuit for the control rod is shown in Figure 36. The rod is dropped by cutting the AC to the coupling solenoid. This may be done in several ways: by the safety tripping circuit which bypasses the AC through a thyratron, by a manual switch, or by the micro-switch (1), which activates the holding relay (3) thereby cutting the AC until the relay is reset. Micro-switch (1) is used to prevent damage to the mechanism. If the rod is raised too high for example by the automatic control it contacts this switch and is automatically dropped. Switch (2) is a S.P.D.T. micro-switch indicating by lights (6) and (7) whether the rod is in or not.

In order to be able to reproduce positions of the rod it is essential that the pinion coupling be reengaged in the same relative position to the ratchet every time after the rod is dropped. An asymetric tooth in the coupling joint limits the engagement to one position in each revolution. The mechanism is so arranged that the coupling solenoids can not be activated unless the position indicator in the control room reads 000. The mechanism for this is shown in detail in Figure 35. The knobs on the two gears (1) and (2) lift up the pivoted arm (3) at each revolution. Only at zero do both knobs pass under the arm at the same time. When this occurs the arm is lifted enough to operate the switches (4) and (5) Figures 35 and 36. Switch (4) Figure 36 releases the mechanical catch of the holding relay (3), while

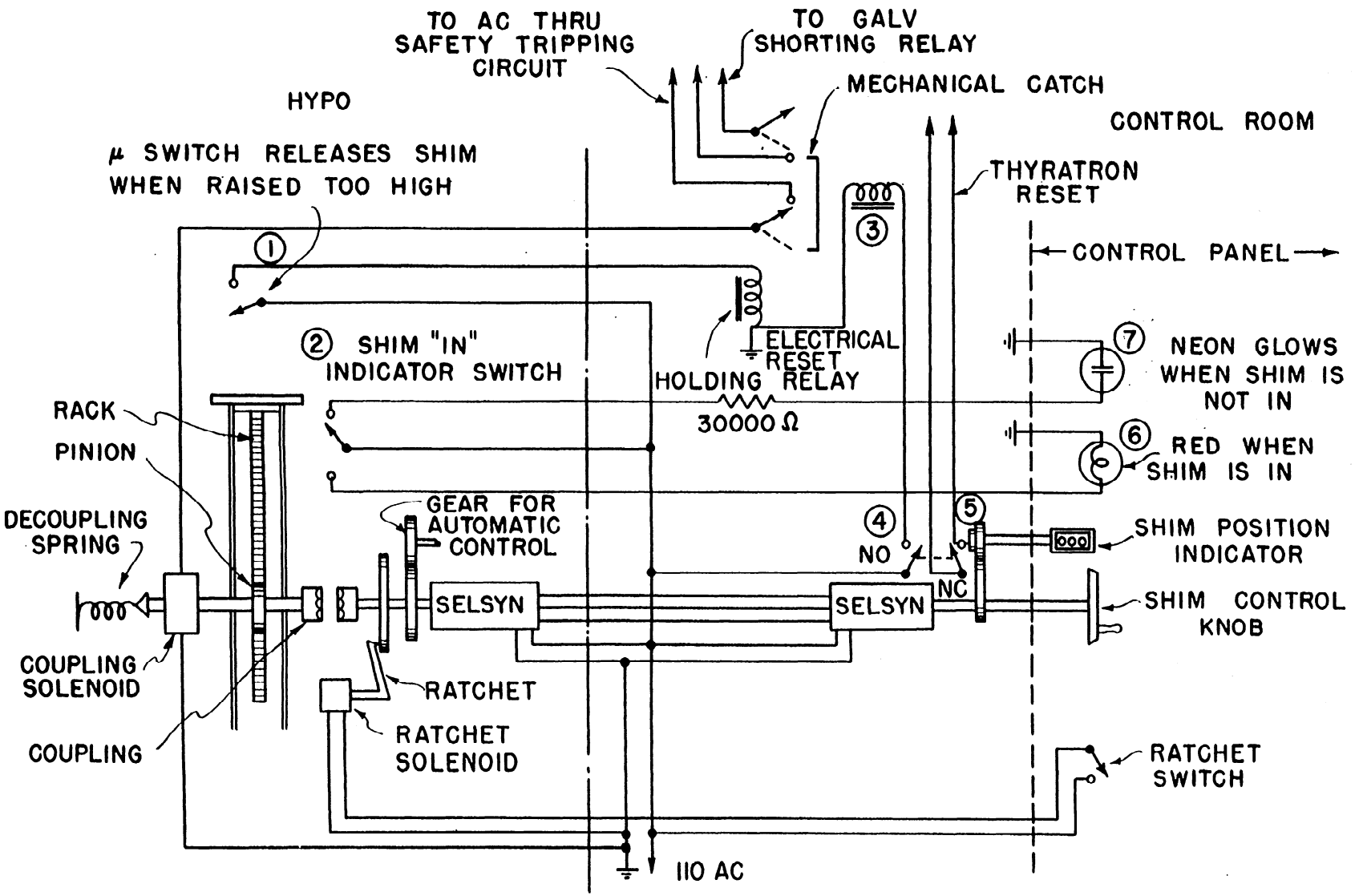


Figure 36

Control rod circuit schematic

switch (5) resets the thyratron safety circuit. The safety circuit is reset, however, only if the indicators of both rods read 000. This is accomplished by requiring that the two parallel micro-switches, one from each rod, simultaneously open the plate supply of the fired thyratron Figure 37.

Air brakes shown in Figure 32 are used for the control and safety rods. Two small dural shafts (1) fastened to the top of the rods hit a piston (2) held up by a spring (3) in a cylinder (4). The brakes operate over the last 4 inches of travel.

Shim rod: A detailed description of this old control rod (Figure 39) may be found in 4.2-1(c) above under low power boiler. It was adapted to the hypo from the low power boiler by extending the screw shaft and outer case.

The motion is controlled by a knob from a center-tapped 200 volt variac on the control panel. The circuit is shown in Figure 40. A reversing switch is connected to the knob in such a way that turning the knob clockwise raises the rod, counter clockwise lowers it. This rod is now mainly used for changing the operating range of the boiler and seldom for control purposes and hence is now called the shim rod.

Safety rod: The safety is shown schematically in Figure 41. It is identical in construction to the two control rods. The circuit diagram is shown in Figure 42.

During operation the safety rod is held "out" by an AC solenoid the core of the solenoid being attached to the rod. An interruption of the current in the magnet brought about manually or by any of the safety circuits allows the rod to fall freely.

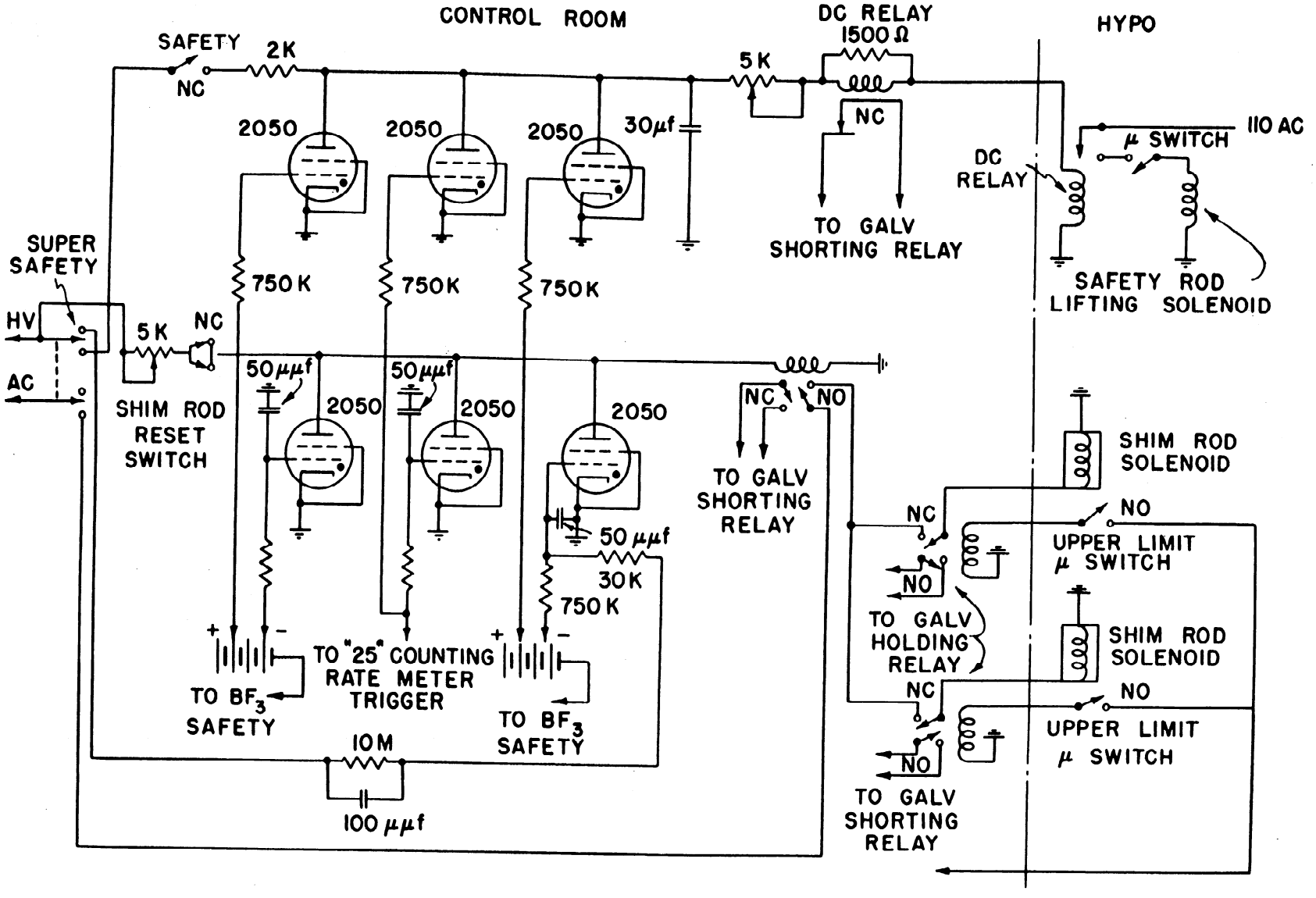


Figure 37

Safety tripping circuit

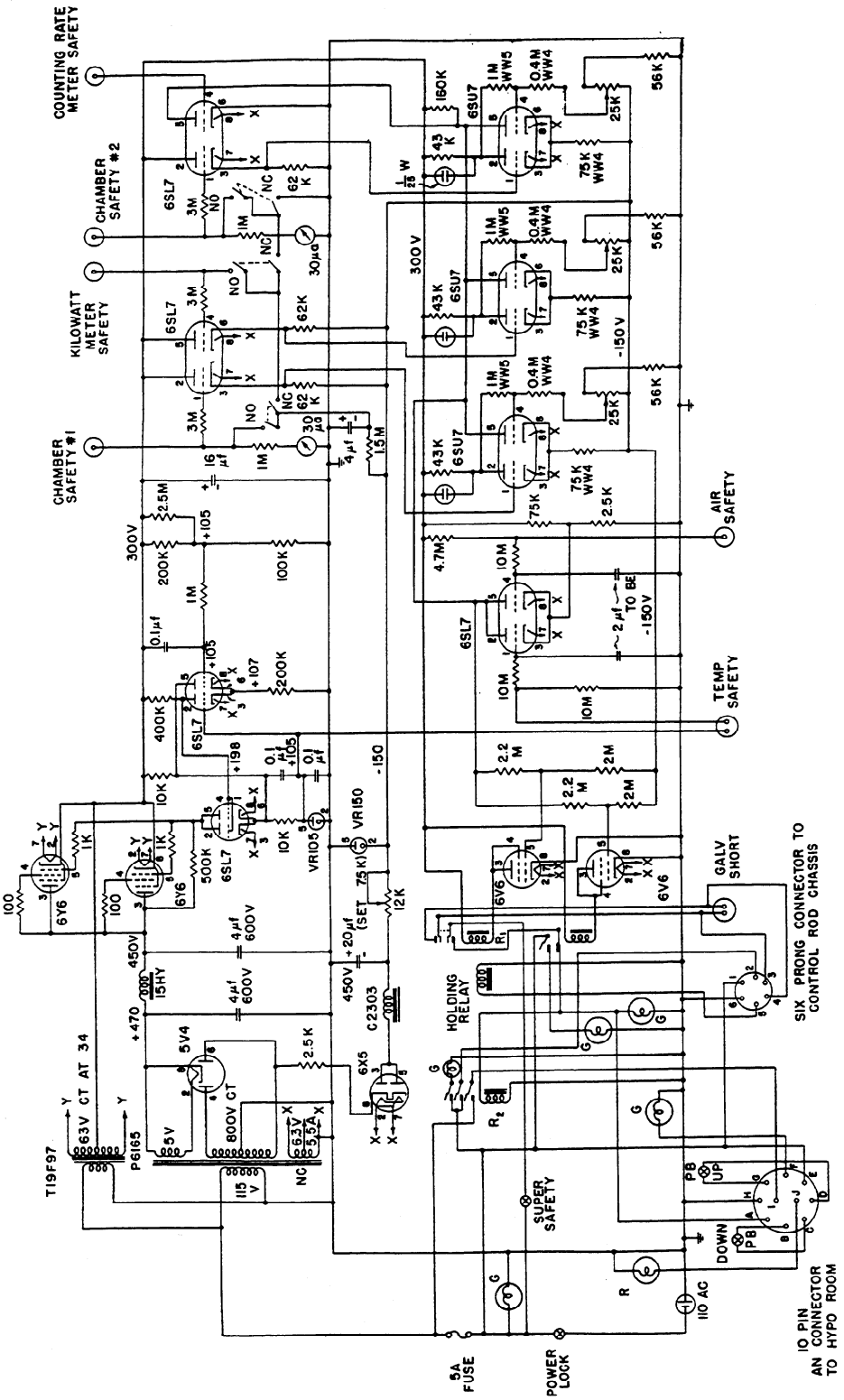


Figure 38

New safety chassis circuit

A	Safety Rod Solenoid
B	Safety Rod Push Button Down
C	
D	
E	Control Rod Power
F	Safety Rod Up (Green Light)
G	Safety Rod Push Button Up
H	Ground
I	Auto Control Power Relay
J	Safety Rod Down (Red Light)

1	Control Rod Power	R_1	SafetyRod Drop Relay
2	Control Rod Solenoids	R_2	Control Rod Drop Relay
3	Galv. Short Relay		
4	Galv. Short Relay		
5	Rod Reset Mechanism		
6	Ground		

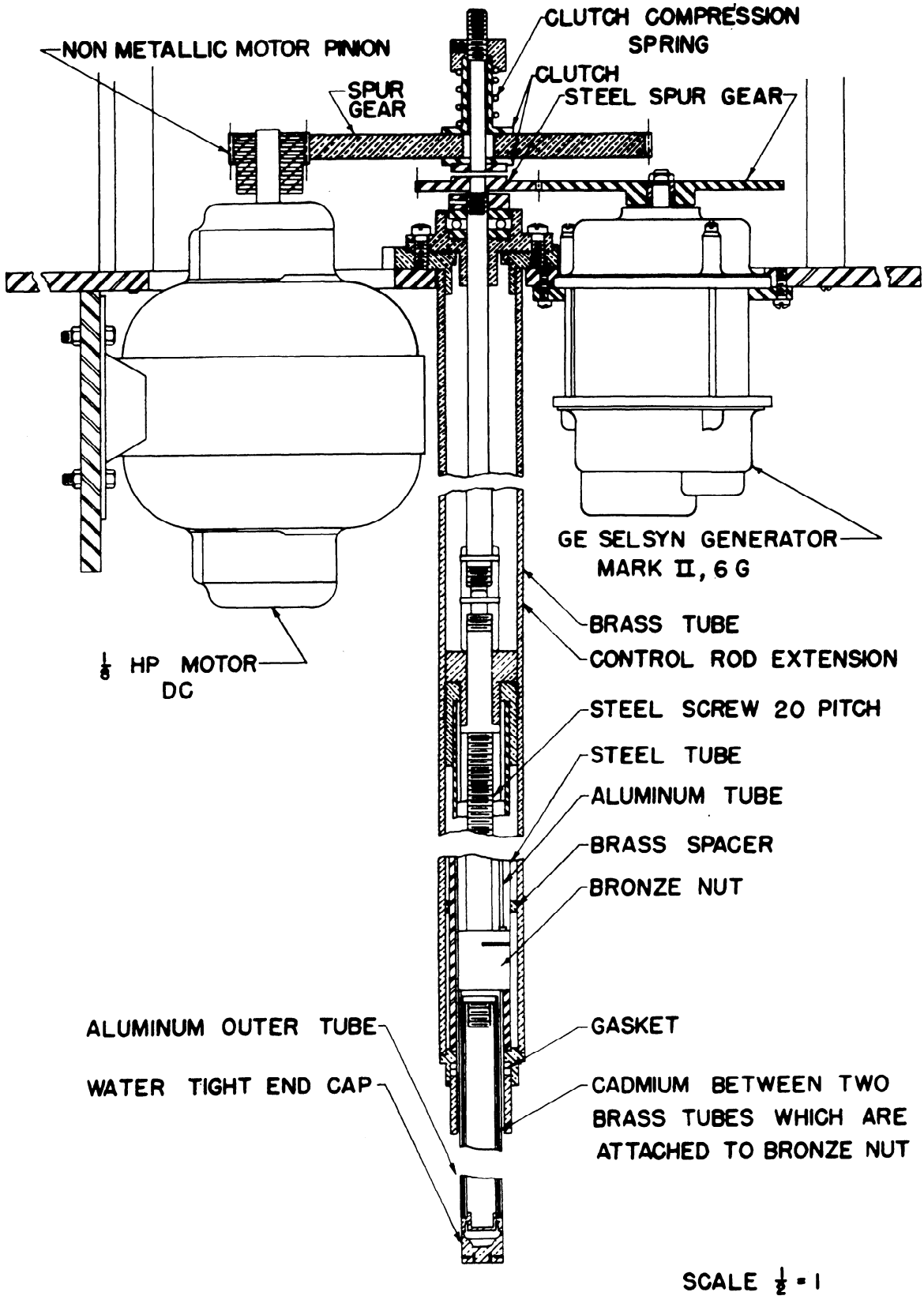


Figure 39

Shim Rod

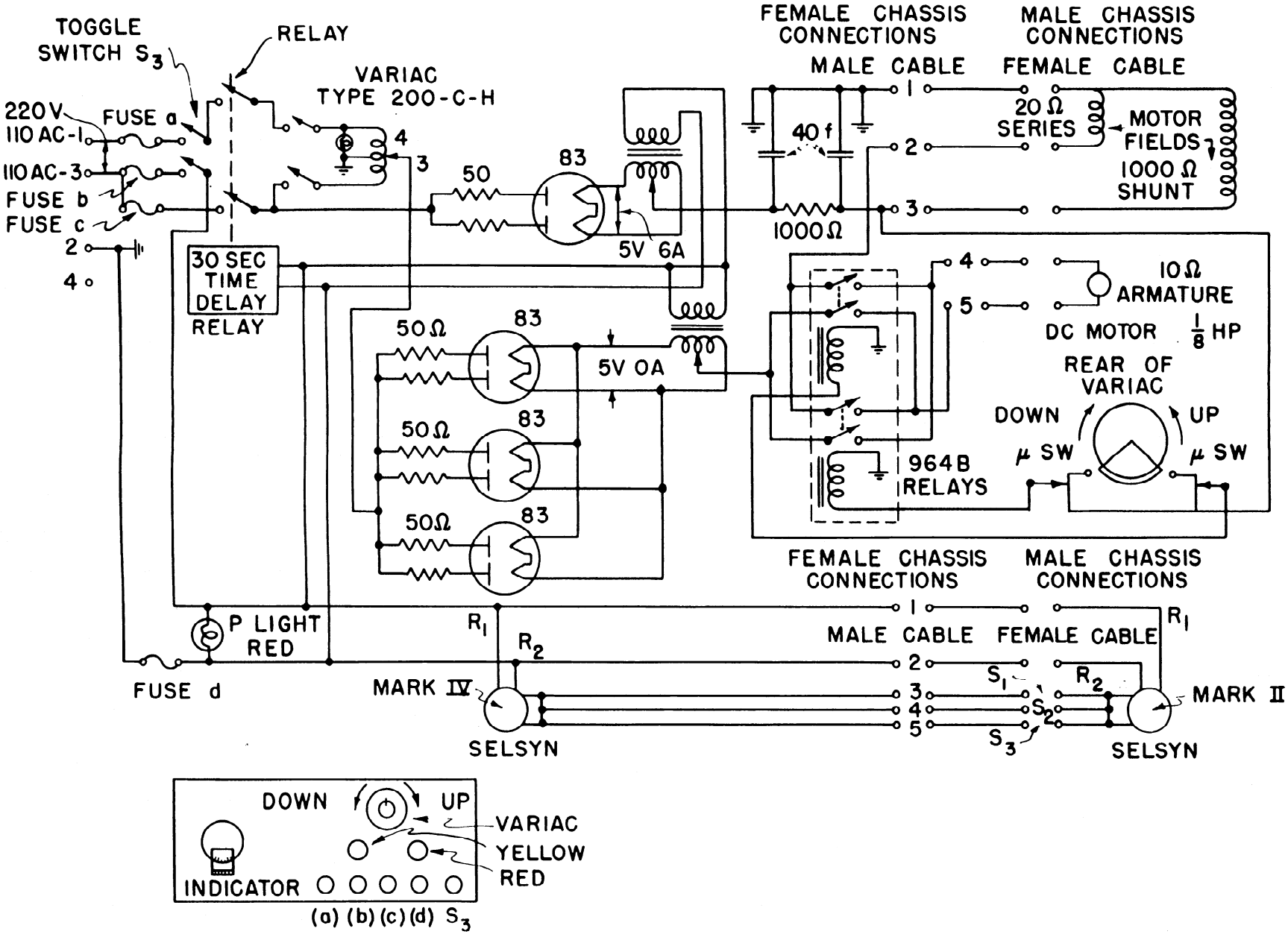


Figure 40

Shim rod circuit

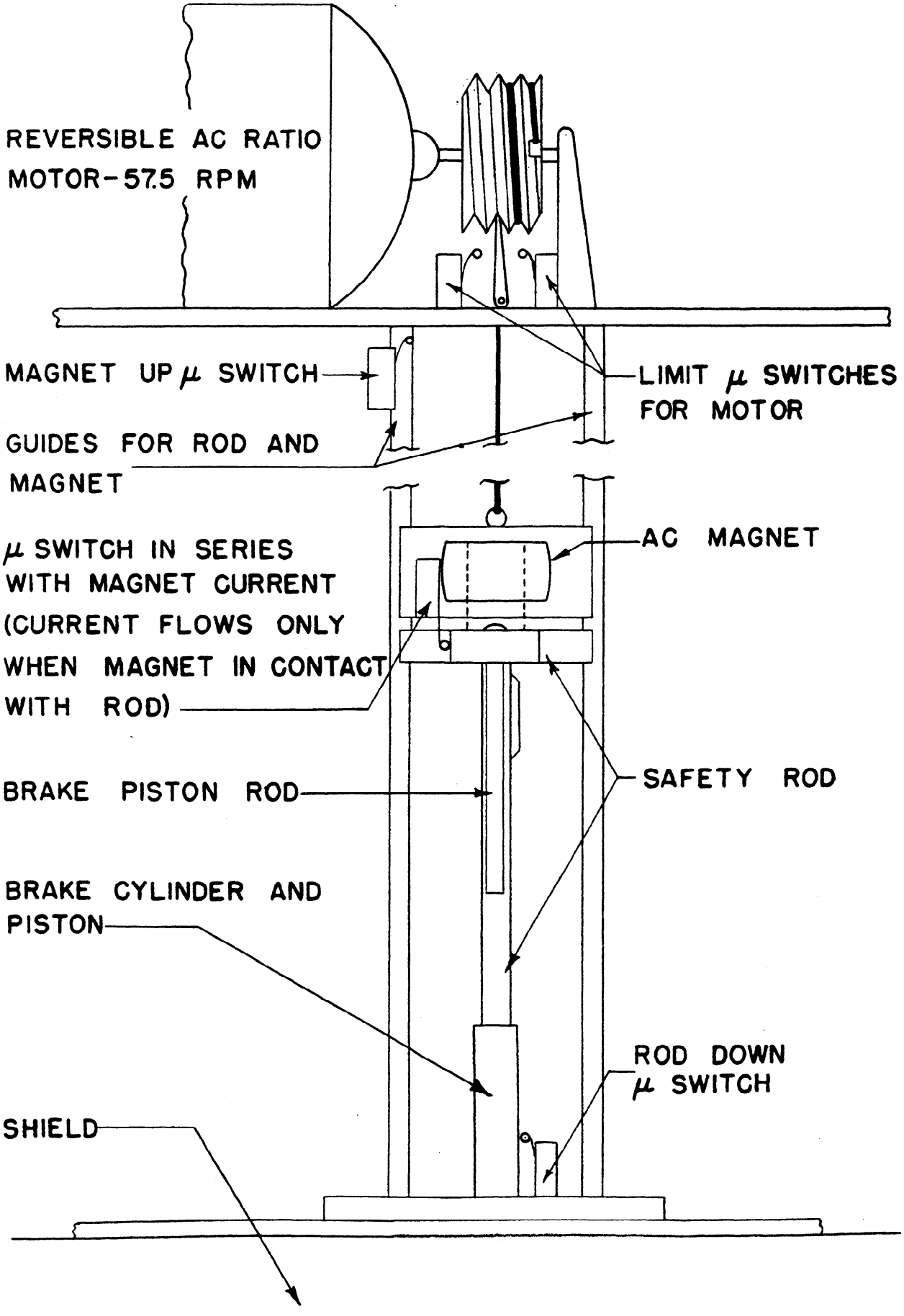


Figure 41

Safety rod (schematic)

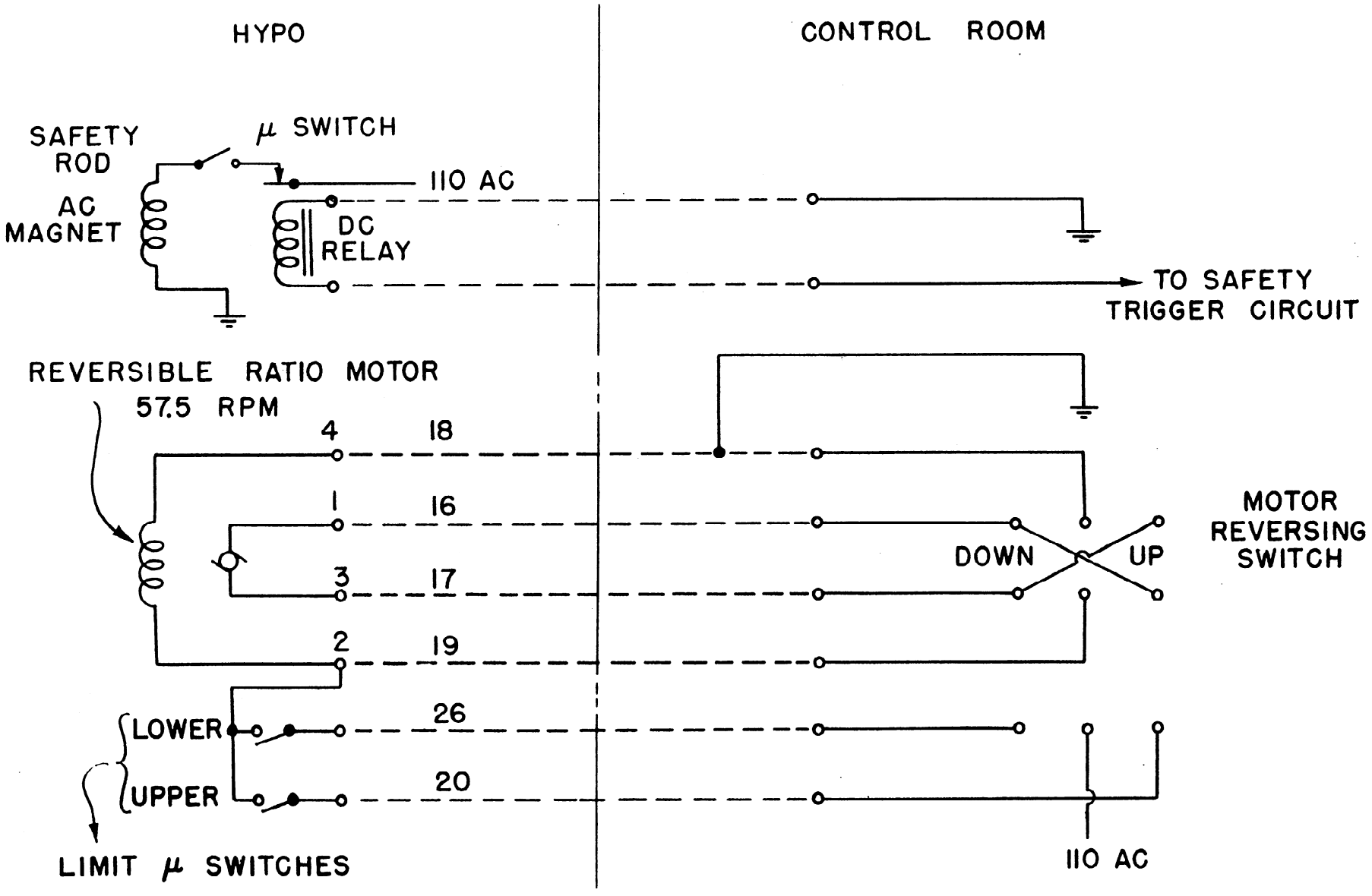


Figure 42

Safety rod circuit.

As shown in Figures 42 and 37 the soilnoid coil is in series with the contacts of normally open D. C. relay and micro-switch. The relay is operated by the safety tripping circuit. The micro-switch closes when the solenoid is in contact with the safety rod, i. e., only when the solenoid core is in place. Without such a device, if the safety tripping circuit were reset after the rod had been dropped, the solenoid would burn up.

The solenoid is raised or lowered by a geared AC motor mounted on the superstructure of the hypo. Limit switches stop the motor when the magnet reaches either its top or bottom positions. As shown in Figure 41 they are operated by a pivoted arm which follows the thread of the cable drum. Two switches operate indicator lights on the control panel, one to show when the magnet is up, the other to show when the rod is down.

In Figure 43 one can see the two control selsyns (the automatic control gear box attached to the left hand one), the control rod mechanism suspended from the upper iron plate and the safety rod mechanism on top. The level indicator with its selsyn and the water inlet are also clearly visible.

(4) Detectors and Indicators

The devices which indicate neutron flux from the hypo are activated by two kinds of ionization chambers - BF_3 and U^{235}.

The most important and useful detecting system is that of the galvanometers. These give a continuous reading, very sensitive to changes in, and proportional to, the neutron flux. The sensitivity to very small variations in power is increased many-fold by using a null method with a high-sensitivity galvanometer. This galvanometer, on full or .1 sensitivity, is kept near its zero position by a slight, continual motion of the shim rods by

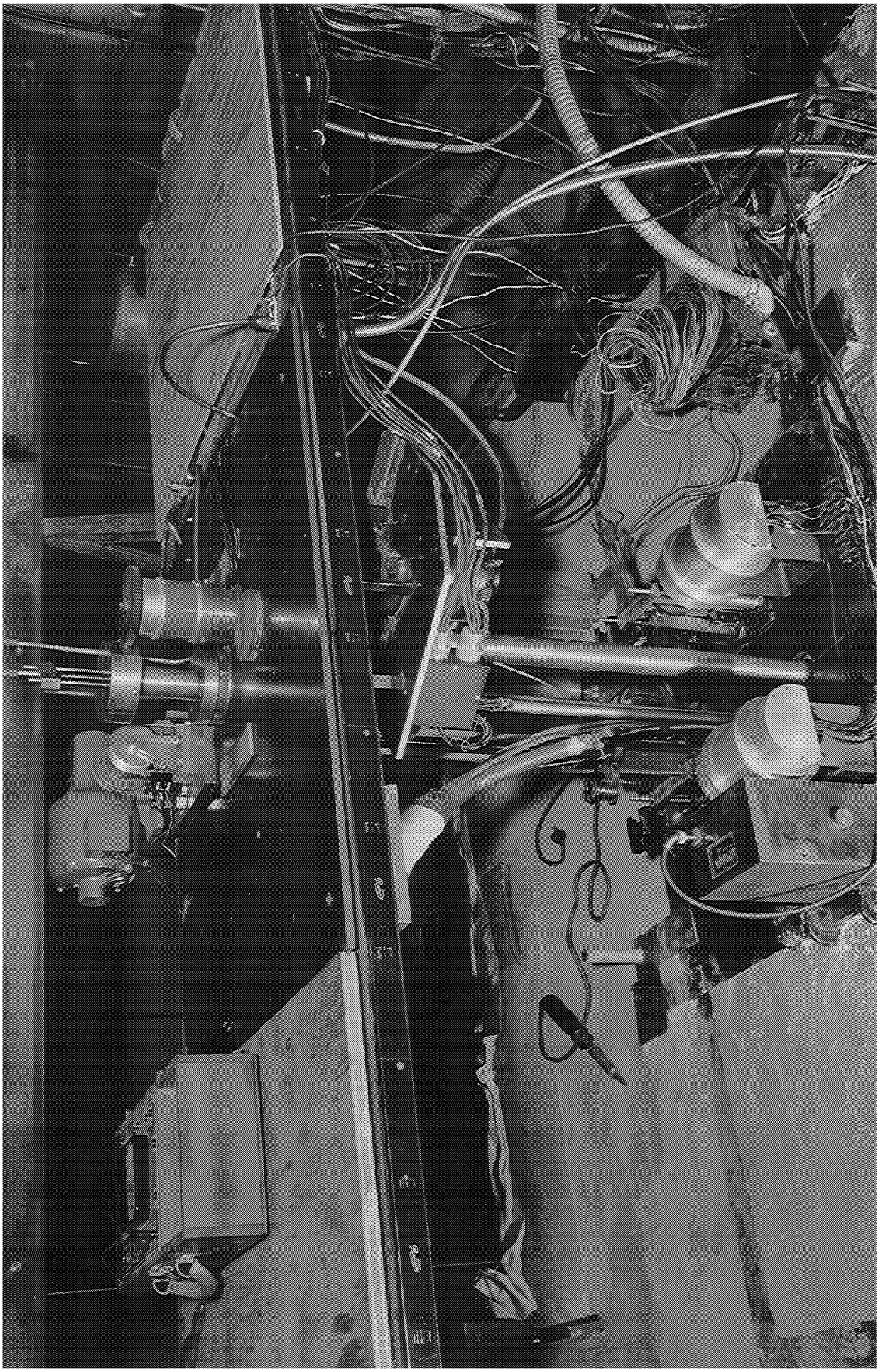


Figure 42

Safety rod circuit.

an operator or the automatic control.

Figure 44 shows the two galvanometers in series, supplied by a large U^{235} coated ionization chamber which will be described later. The chamber, which for normal operation is pulled out to the edge of the tamper, is in a high enough flux so that the ionization current is of the order of 5×10^{-6} amperes per kilowatt and the first galvanometer, which is deflected by the total current, must be shunted to 1/1000 of its maximum sensitivity for any powers over 1 kilowatt, (see 4.3-3(5) for planned modification). This, of course, makes it insensitive to changes of even several percent. All of this ionization current goes through the differentially connected galvanometer also, but its spot is kept on scale by an equal and opposite current. This current is supplied by a continuously variable source of emf obtained from a potentiometer, applied through a resister of the proper value. The deflection sensitivity of the differential galvanometer is 5×10^5 millimeters per kilowatt, so by the null method, a change of neutron density of one part in five-hundred thousand is detectable at this power and one part in fifty thousand controllable. This sensitivity, however, is proportional to the power of operation and is therefore less at low powers. A protecting relay system has been installed to short out the differential galvanometer automatically if any of the controlling rods should drop unexpectedly (Figure 45).

Since the chamber is only about 45 centimeters from the sphere, ionization due to the gamma-activity of the accumulated fission fragments was expected to produce a variable and appreciable background. This has been found to be negligible.

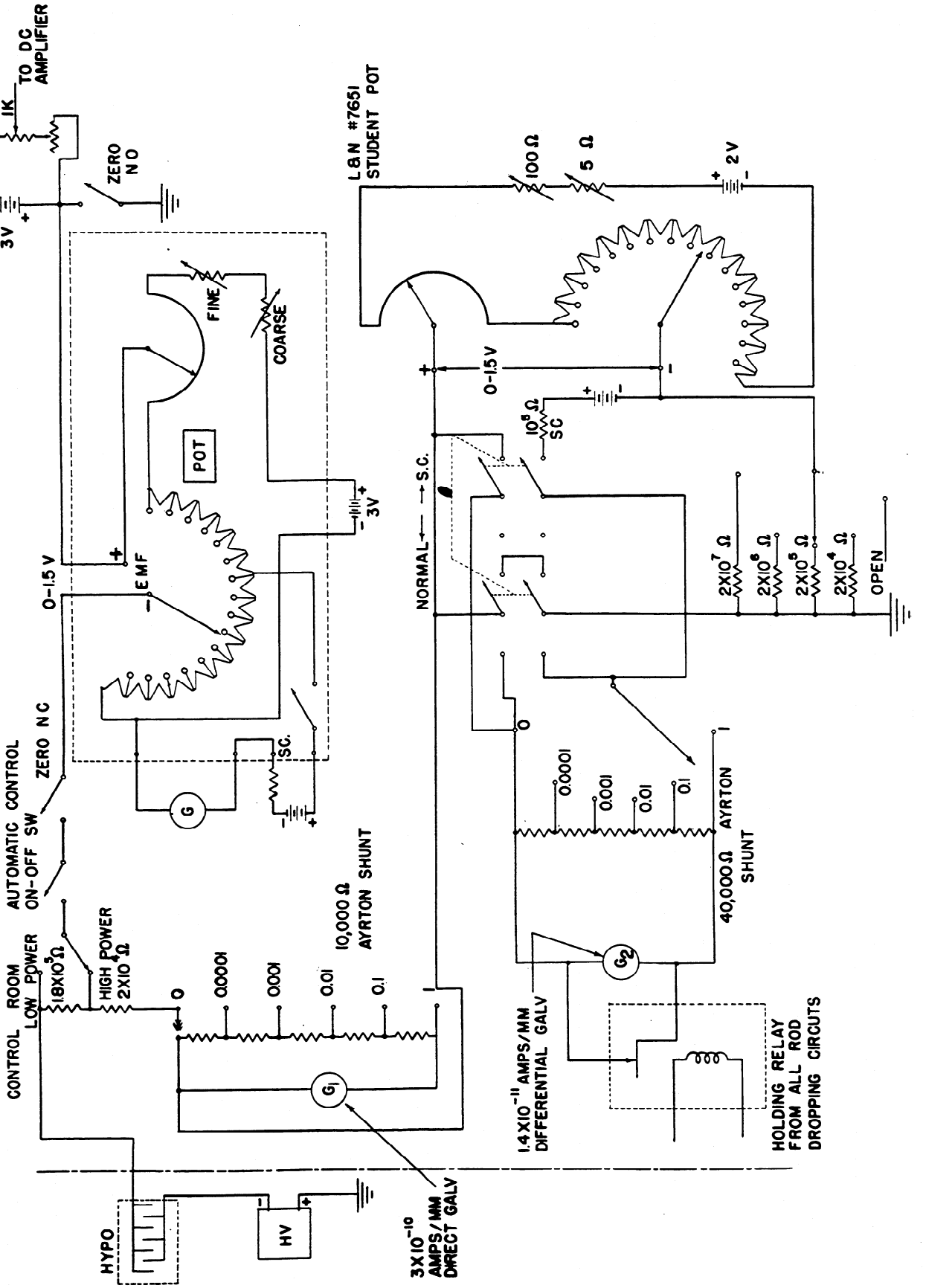


Figure 44

Galvanometer and automatic control input circuit

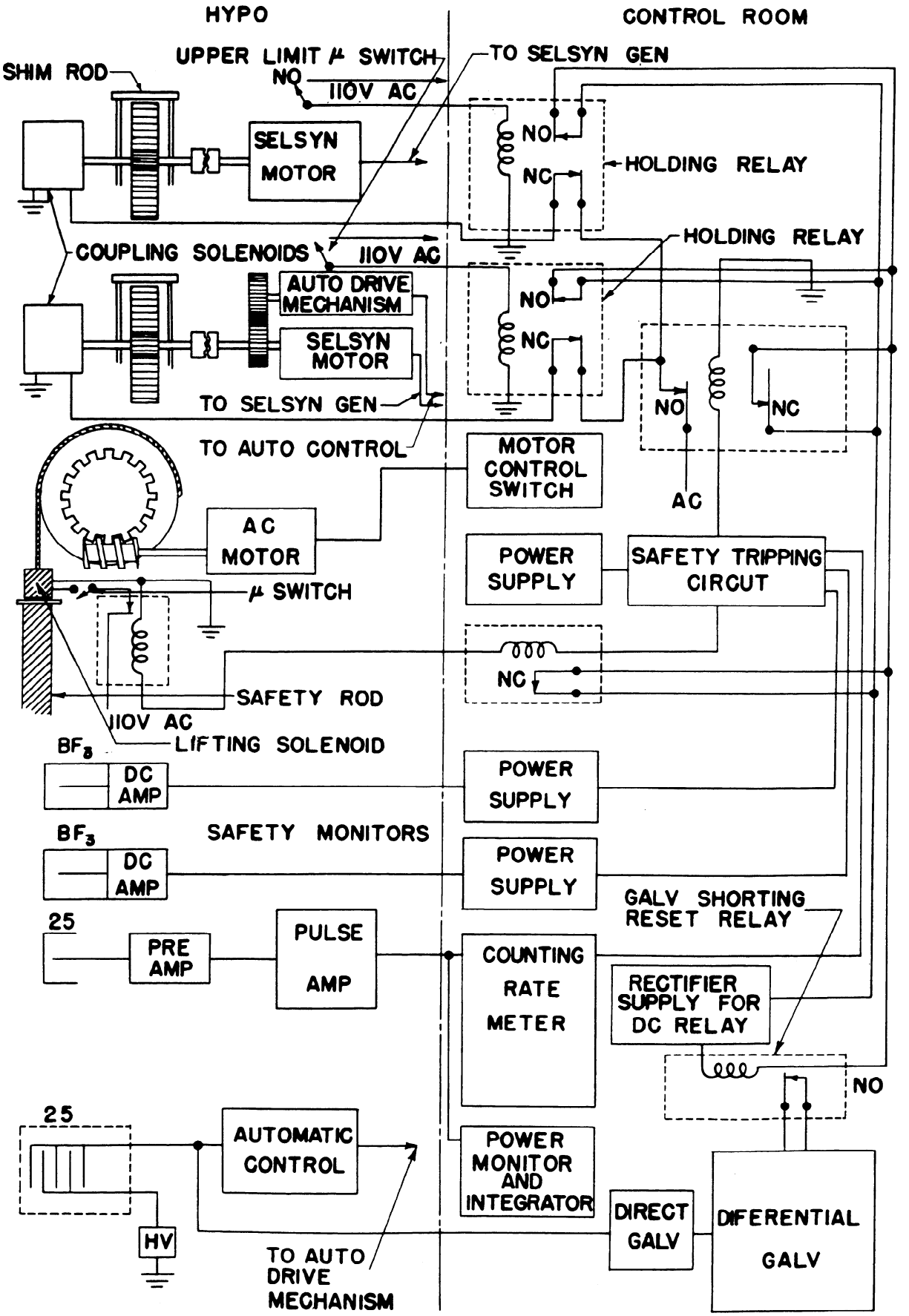


Figure 45

Safety circuit

It was desirable to eliminate ion-producing processes which result from past history of the boiler, or from the total (nv)t having passed through the ionization chamber. This meant using a construction material for the chamber which gave very little residual activity after a strong bombardment. It had been found at Chicago that if ordinary "black" or cold rolled iron were used, practically the only activity present was due to Mn impurities. So the chamber Figure 46, is built entirely of this material.

The chamber was designed with paralleled plates connected as shown to permit rather large surface area in a convenient volume so that the large ionization currents required for high sensitivity could be obtained. Another type chamber recently used to replace the BF_3 chambers is shown in Figure 47.

The chamber, Figure 46, contains a total of 184 milligrams of U^{235}. All plates except those on the ends are coated on both sides. The coating is the residue left after heating the original 353 milligrams of 63.1 per cent enriched U_3O_8 put on in the form of nitrate with a zapon binder.

The small U^{235} chamber which has been used to determine the linearity of the galvanometer system is used to integrate the total power. This is accomplished by setting the discriminator of a scaler to a value which will give some predetermined number of counts for a kilowatt-minute of operation. This system, recorded on a modified mechanical counter through a scale of 256, is never turned off, and is read at the control panel at the beginning and end of each run. This chamber also operates a counting rate meter model 100 which contains a

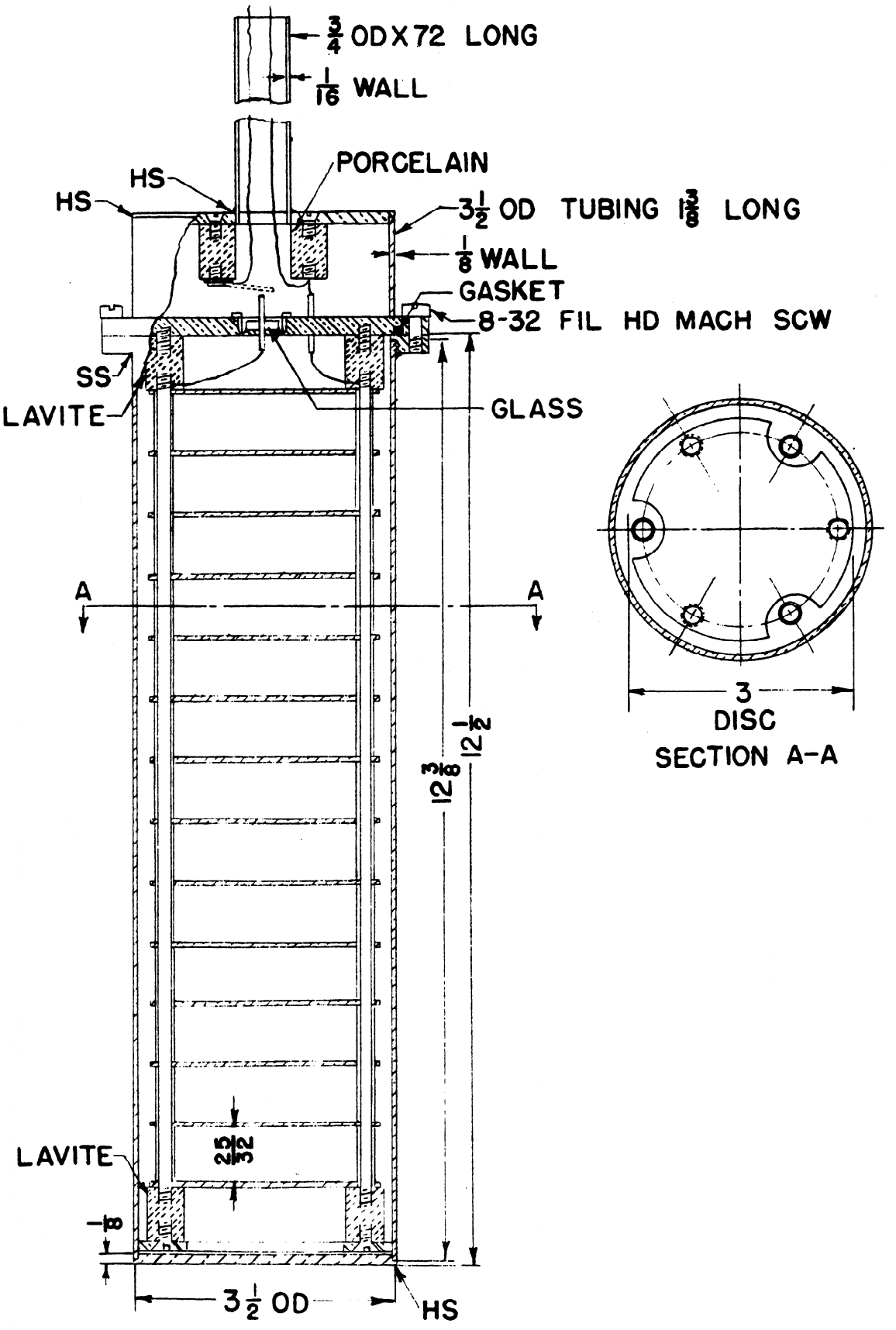


Figure 46

Large U^{235} Chamber

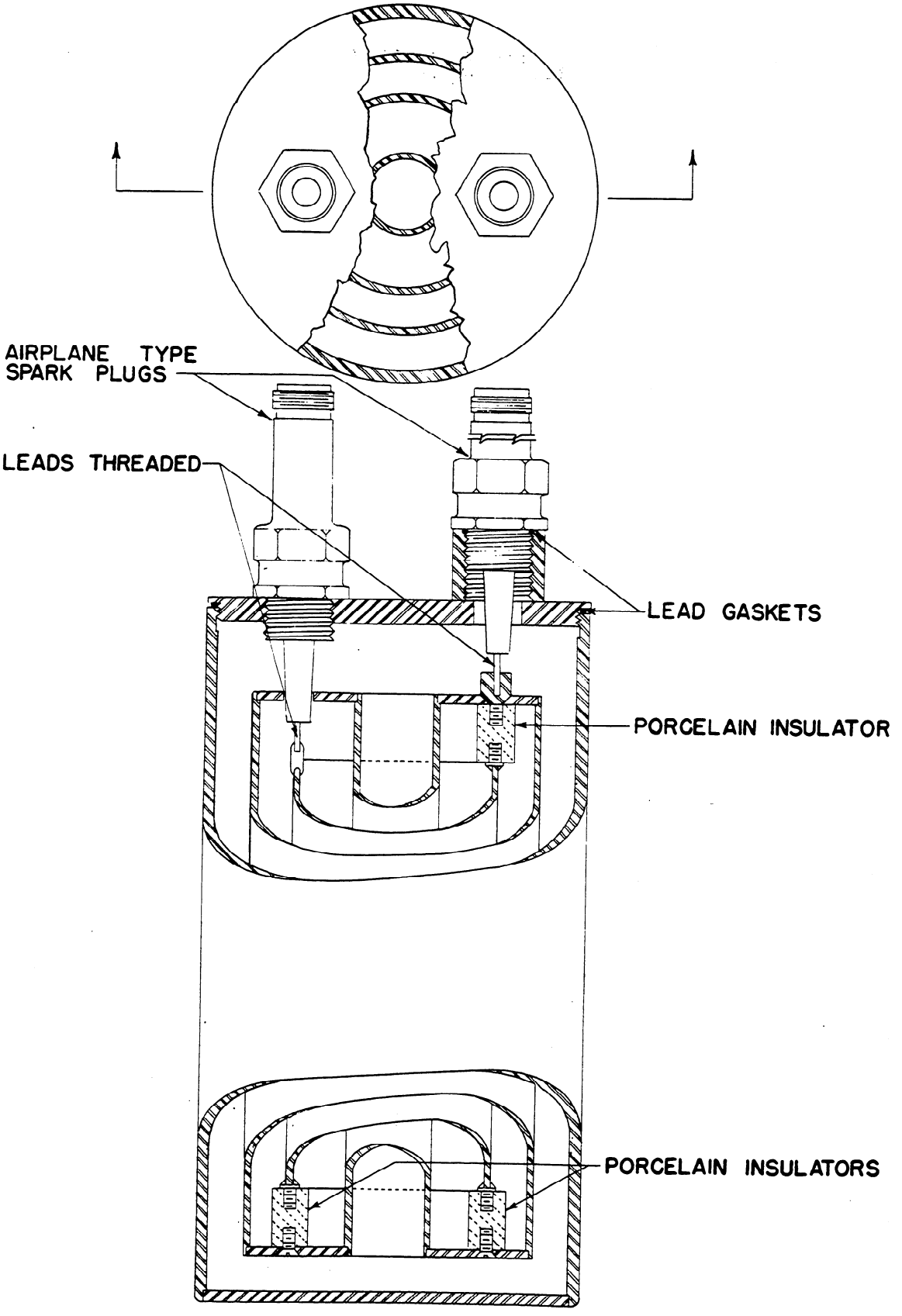


Figure 47

New Type U^{235} Chamber

rod-dropping circuit. (Volume I, Chapter 1).

This U^{235} chamber consists of an aluminum foil in the form of a cylinder 1 inch long by 5/8 inch diameter, coated with a thin layer of 63.1 per cent enriched U. There are 1.15 milligrams of U_3O_8, making .613 milligrams of U^{235}, and a consequent cross-section of roughly $.85 \times 10^{-3}$ square centimeters. The chamber is connected to the preamp by a 3/4 inch O. D. 7.5-foot dural tube. Both chamber and tube contain argon at about 20 pounds per square inch (absolute). The signal lead, a 0.008 inch piano wire, connects the chamber to a Sands Model 101 preamp and 100 amplifier. See Volume I, Chapter 1 of Los Alamos Technical Series.

Another midget U^{235} chamber can be used for flux measurements in the thermal column or as a fixed monitor. It was made by coating U^{235} on a platinum foil which was then rolled into a cylinder and sealed into a glass tube. The tube was filled to a pressure of one atmosphere with pure argon and sealed off. A photograph of this type of chamber is shown in Figure 50. The chamber is mounted at one end of a 7/8 inch O. D. aluminum tube 8 feet long so that it can be placed in the middle of the thermal column through one of the small side ports shown in Figures 28 and 30.

Figure 48 shows the power calibration curves for the large U^{235} chamber and the small integrating chamber.

(5) Automatic pilot

For very accurate control of the neutron level almost continuous slight motion of the controlling rod is necessary. An automatic control has been made to relieve the operator from

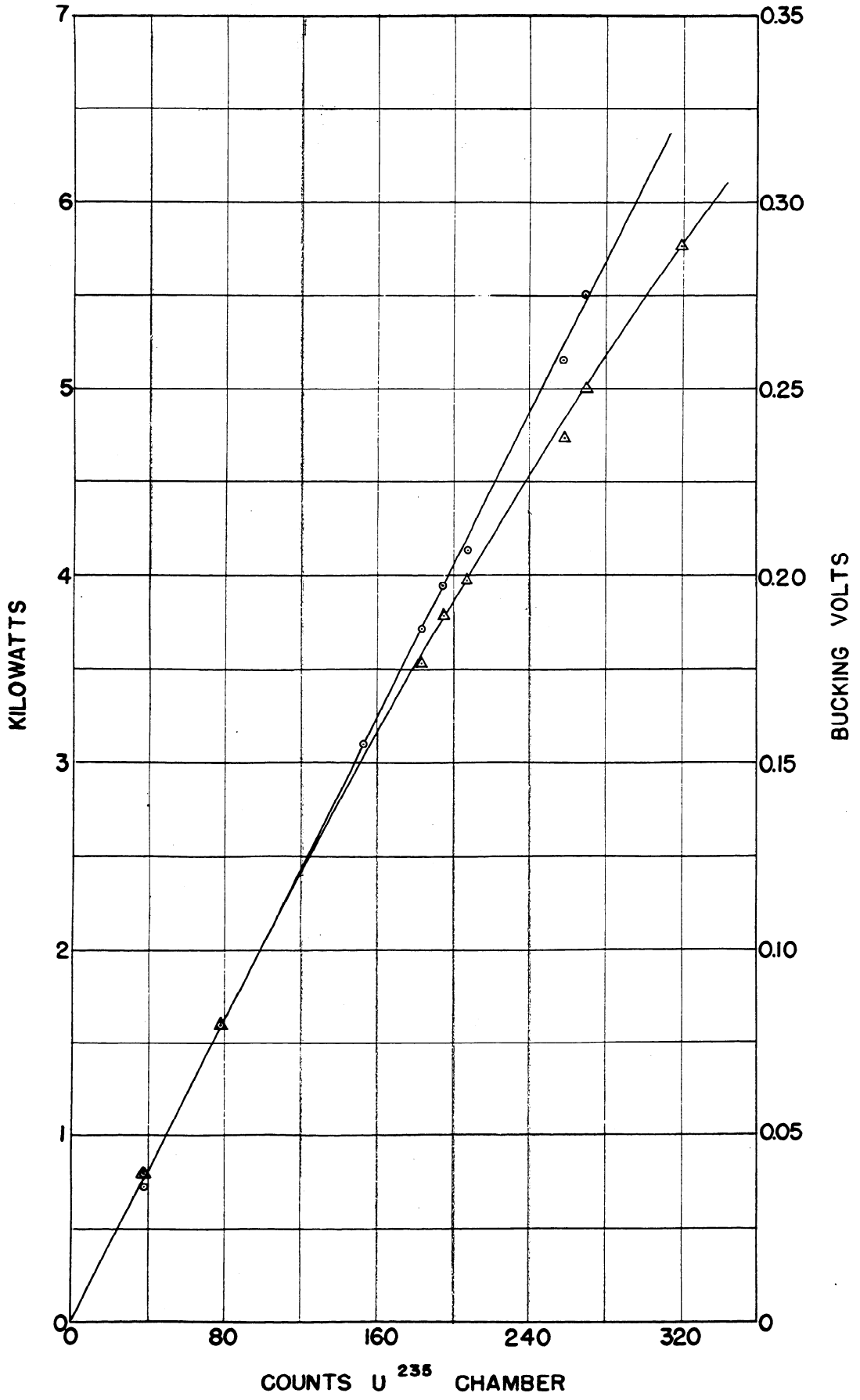


Figure 48

Power Calibration

⊙ Kilowatts vs U^{235} Chamber

△ Bucking Voltage vs U^{235}

this rather fatiguing job

Figure 51 shows a schematic layout of the control. The system uses the current from the large U^{235} chamber (Figure 46 which also supplies the current for the control galvanometers. The control system consists of (1) a power determining device (resistor in Figure 44), (2) a DC amplifier and mixer (Figure 52), (3) and AC amplifier (Figure 53), and (4) a regulated power supply.

The intensity level at which the control operates is determined by the off-balance voltage applied to the DC amplifier. The pilot then causes the intensity to rise by pulling the shim rod out until the voltage developed across the imput resistor cancels the applied voltage. Any subsequent fluctuations of the boiler will cause the control to move the rod in such a direction as to remove the unbalance.

Any voltage change occurring across the imput resistor is amplified by the DC amplifier and applied to the mixer or converter. The mixer is essentially a linear gate circuit which delivers a 60 cycle output whose amplitude is proportional to the amplitude of the DC and whose phase is determined by the polarity of the DC. The converter output is fed to the AC amplifier where it is built up until enough power is available to drive a small reversible two phase motor. The motor drives the controlling rod rack and pinion through a train of gears with a safety release mechanism (Figure 34).

The unbalanced voltage is obtained by a standard potentiometer Figure 44. The dial of the potentiometer reads power directly to a few watts. The accuracy of the dial calibration is assured

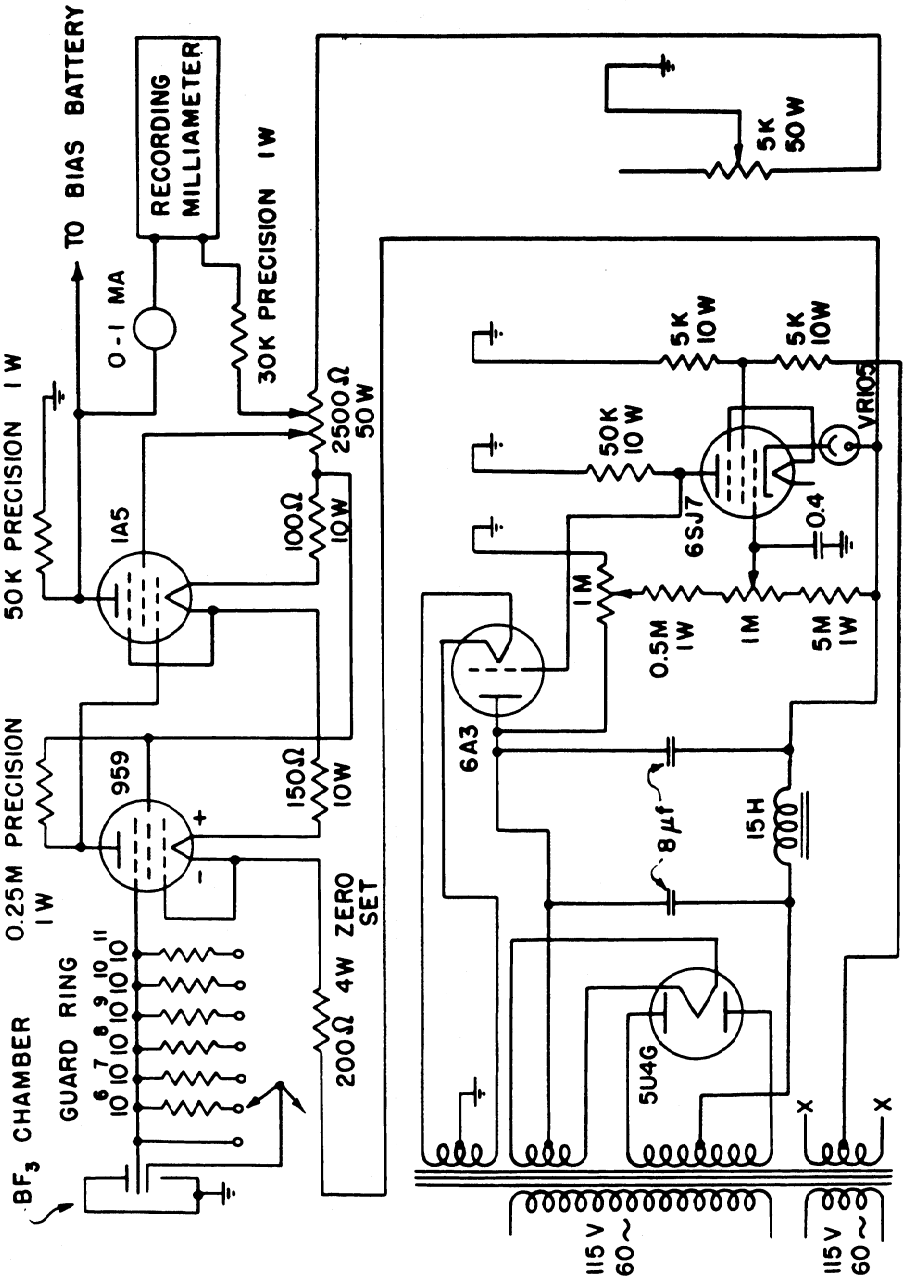


Figure 49

D. C. Amplifier - safety monitor

Figure 50

by checking with the standard cell. Once the control is set the power level can be maintained at about .01 per cent with only an occasional slight drift.

(6) Safety devices

There are three independent detectors which can be adjusted to drop the safety and control rods at any predetermined neutron intensity Figure 45. Two of these are BF_3 chambers connected to DC amplifiers Figure 49. The other is the above mentioned small U^{235} chamber and counting rate meter which includes a safety tripping flip-flop circuit. The measured overall time required to drop the rod is 0.42 seconds; this is made up of .378 seconds for the rods to drop by gravity. .0420 seconds from the lag in the electrical components (relay and solenoid).

The safety circuits Figure 37 are arranged with two bias batteries. When the intensity goes up to a predetermined value the normal safety rod is released by firing a thyratron. If the intensity should still continue up to a point 50 per cent higher, another thyratron with its grid more highly biased is fired and causes both control rods to drop. This system has been most satisfactory. The safety rod only, or both control and safety rods, can also be dropped manually by switches on the control panel. These switches are shown as "safety" and "super-safety" in Figure 37. The safety-rod thyratron is automatically reset by a condenser when the neutron intensity gets sufficiently low (Figure 37). A delay in reenergizing the lifting solenoid has been described in the section above on the control rods. For the control rods the thyratron continues to conduct until the plate lead is opened simultaneously by the two switches labeled shim rod reset (Figure 37) as mentioned above. Recently a somewhat simplified safety circuit using hard vacuum tubes

has been used (Figure 38).

During the operation of the boiler, flushing air must always be flowing, to prevent the formation of an explosive mixture. In addition, cooling water may or may not be flowing depending on the power of operation. Since it is always possible either through mechanical failure or through carelessness of the operator to start a run without air or water, additional preventive safety devices have been installed to protect equipment from possible damage.

In series with the light that indicates the flow of air is a relay in the grid circuit of a thyratron. This thyratron is in parallel with those of the safety monitor system. When the air is left off, or is not flowing sufficiently to light the indicator, the thyratron is fired which drops the safety rod. The criterion in the case of the flow of water is the temperature of the "soup." Current from a thermocouple in the "soup" is put through a galvanometer, and the photo tube is placed in the path of the spot, so that when a temperature exceeding 85 degrees is reached the photo tube "fires" another thyratron again dropping the safety rod.

In the same category of preventive safety devices, are included those to prevent unauthorized personnel from tampering with the control mechanisms or operating the boiler. The power for the operation of the rods is controlled by a locking switch, the key to which is available only to authorized personnel. To prevent the manual raising of the rods without using the control panel the rods have been enclosed in a small removable structure normally kept locked. This structure is not shown in Figure 43

4.3-3 Operation

(1) Approach to critical

A solution containing approximately 56 grams of U^{235} per liter was prepared and a system arranged so that the solution could be added to the sphere in known volumes or portions withdrawn for mixing.

The method used was to run a "Saran" tube to the bottom of the sphere through the level indicator tube. Then by means of a vacuum pump part of the solution could be raised into a large graduate and known quantities of solution added and mixed before lowering it into the sphere. More complete mixing with the solution already in the sphere was accomplished by raising and lowering $2\frac{1}{2}$ liters ten times between the graduate and the sphere.

Counts were taken with the detecting chambers when approximately 3, 6, 9, 10, 11, and 12, liters of solution were in the sphere. A plot of the reciprocal of the counting rate versus the mass of U^{235} in the sphere gave an indication of the expected critical mass. Six more smaller additions brought the boiler to critical with 808 grams of 14 per cent enriched Uranium. It should be noted that all these smaller additions as well as those for the rod calibration mentioned below had to be done at constant volume in the sphere in order to have identical geometrical conditions.

(2) Rod calibration

From the reactivity equation for the water boiler described in 4.2-3(4) above the relation between reactivity or excess K and the boiler period is known. Independent calculations based on the cross section of the solution components and absorption by the stainless steel container and cooling coil give the equation

$$\delta K = K - 1 = 1.219 \frac{m}{m + 177} - 1 \quad \text{(See Figure 54)}$$

relating the excess reactivity of δK to the total mass (m) of U^{235} in the sphere. This equation has an initial slope of 222 and a final slope of 196 i. e., the effectiveness of one gram of U^{235} becomes less as material is added from critical to the final amount of 870 grams of U^{235}. This shows the greater meaningfulness of a reactivity unit as compared to using grams of U^{235} as a unit. The microre suggested by Fermi is used as a measure of reactivity. This unit was used in all calibration work, a microre being taken as $K \times 10^6$.

The apparent loss of reactivity per gram of U^{235} with increased concentration was observed during the rod calibration since the effect of the rods appeared to change with equal additions of U^{235}. This difficulty was overcome in the calibration since there was a considerable region over which the calibration curve for each rod was linear. It was therefore possible to connect the early "out" position section of the calibration curve to the later "in" position section by a shift until the linear portions coincided; i. e., the intercalibration of the rods was done by comparing one rod operating on the curved characteristic with the other working on the linear portion, as the U^{235} concentration was increased.

(3) Temperature effect

A determination of the temperature coefficient for the power boiler was made over a wide range. The results are shown in Figure 56. A negative coefficient of 262 microre = 1.33 gram of U^{235} equivalent per degree centigrade was obtained.

The temperature of the solution as a function of boiler power is shown in Figure 57.

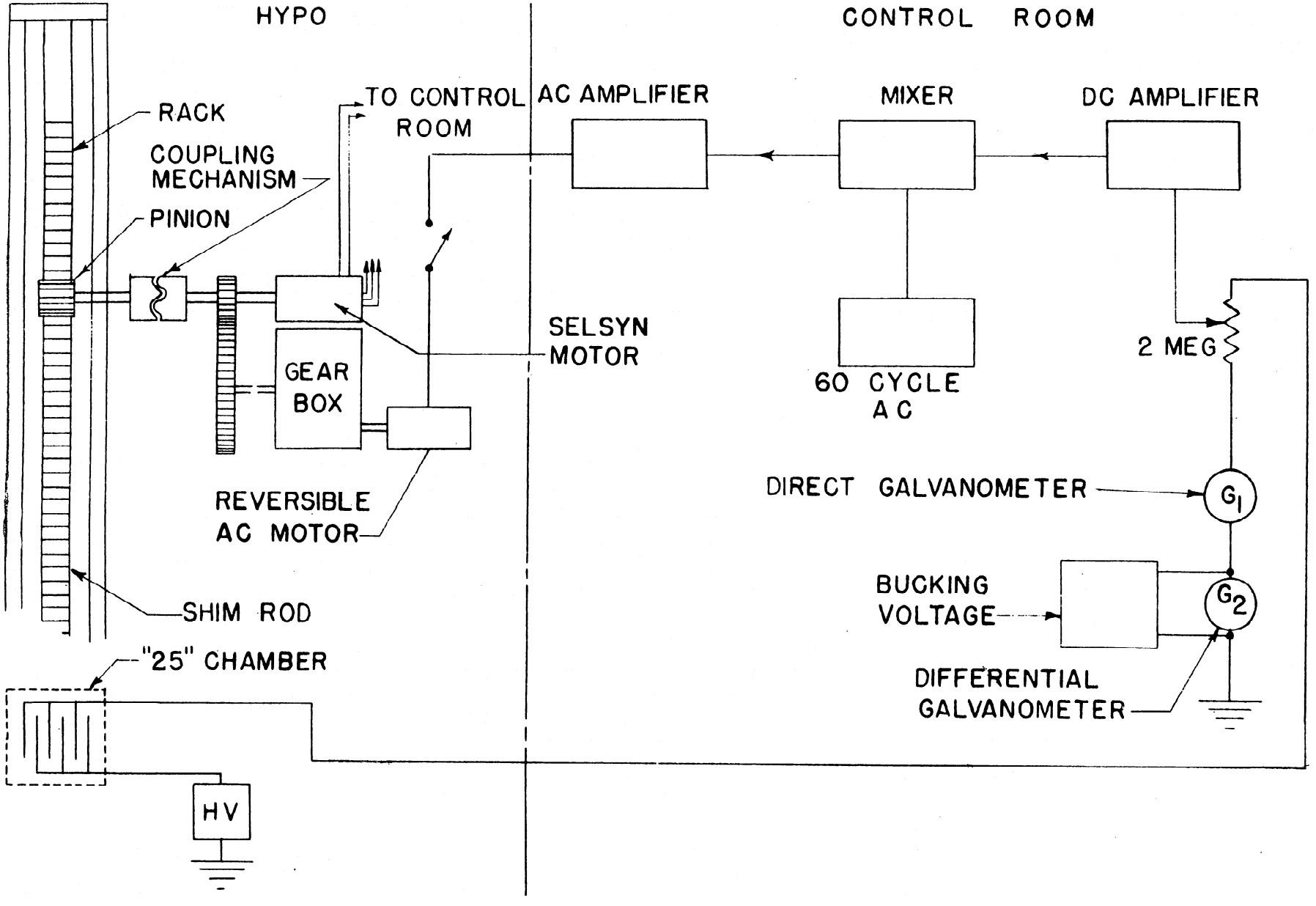


Figure 51

Automatic control diagram

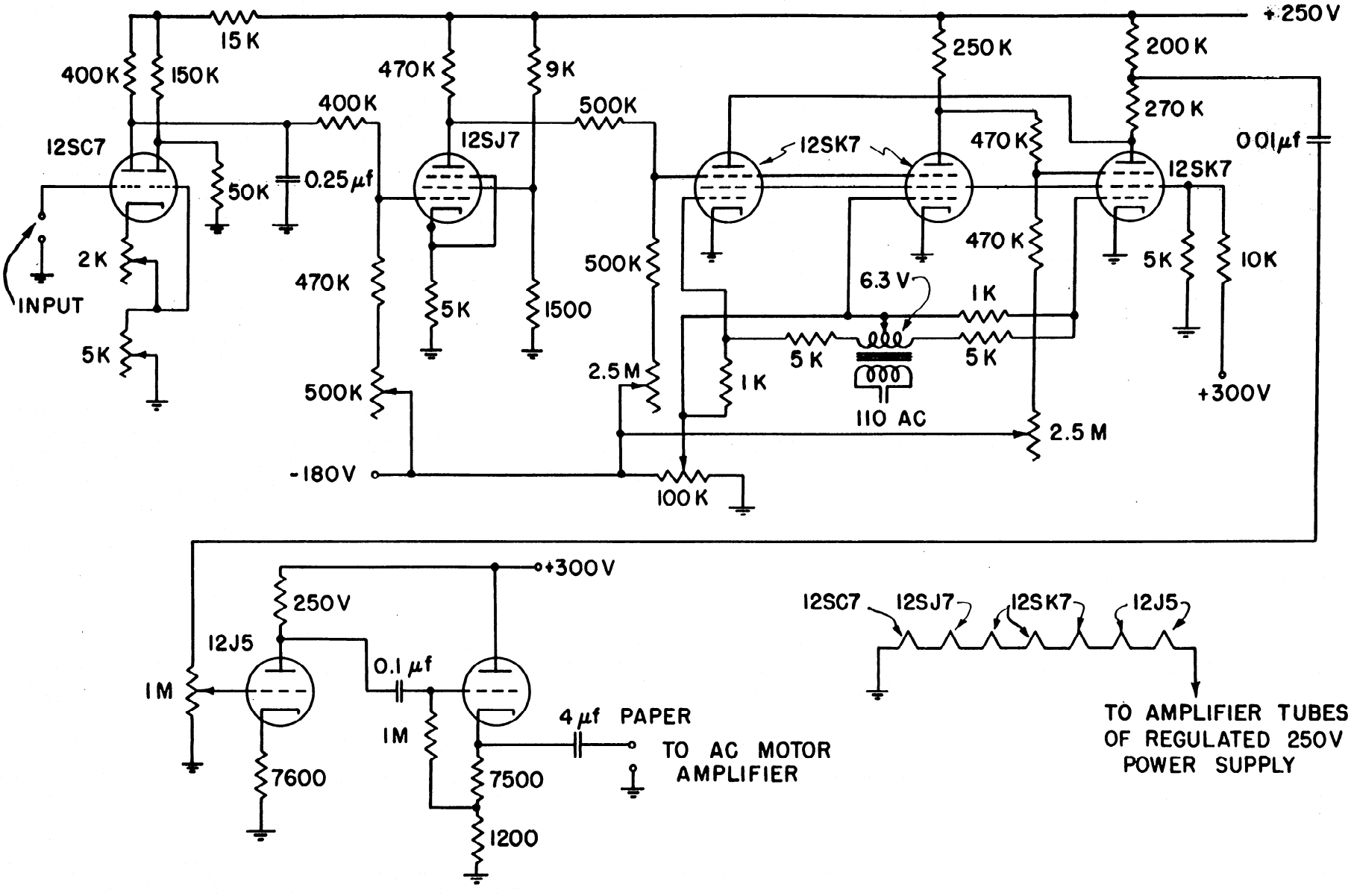


Figure 52

D. C. Amplifier and Mixer for Automatic Control

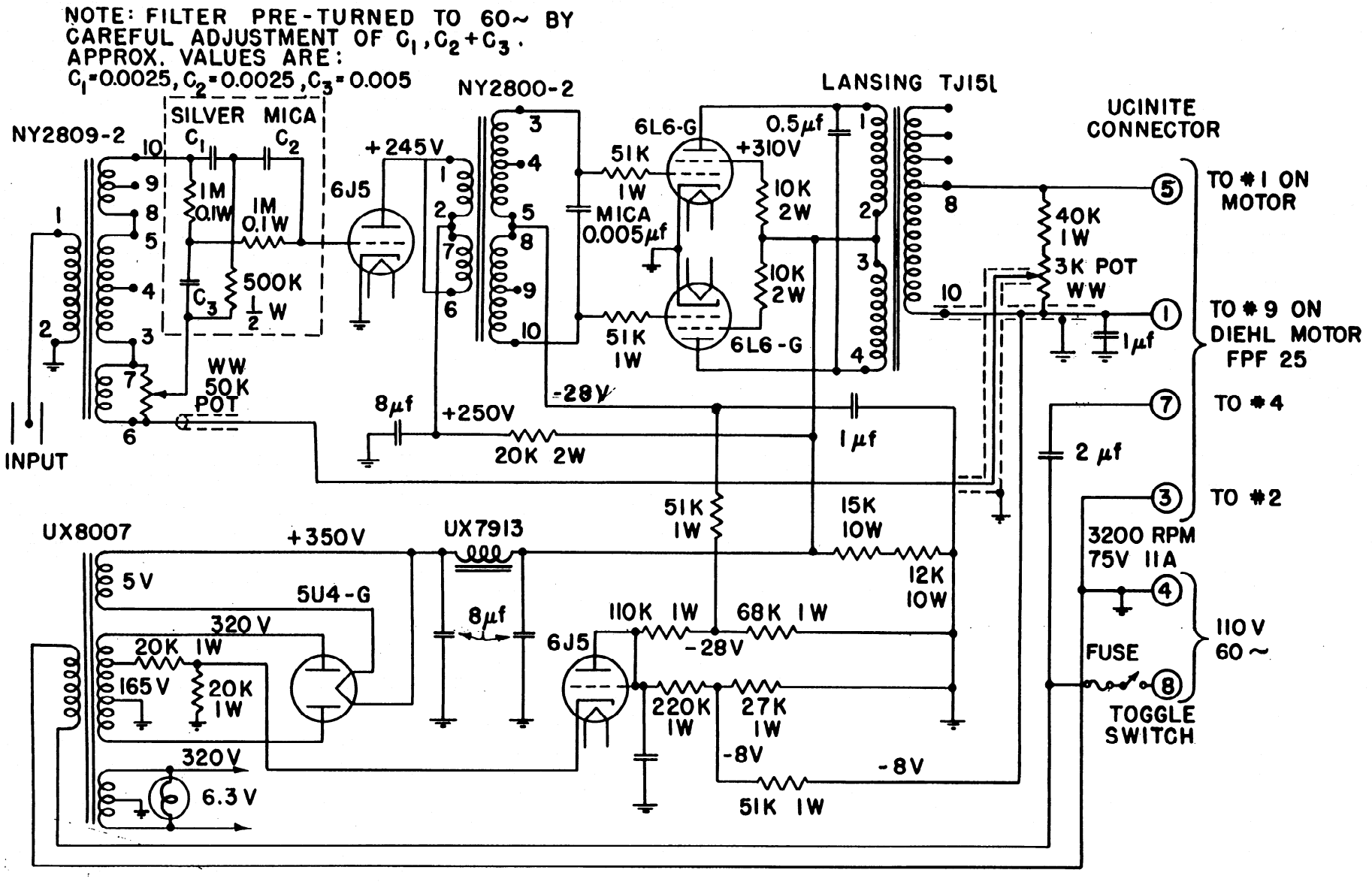


Figure 53

A. C. Amplifier for Automatic Control

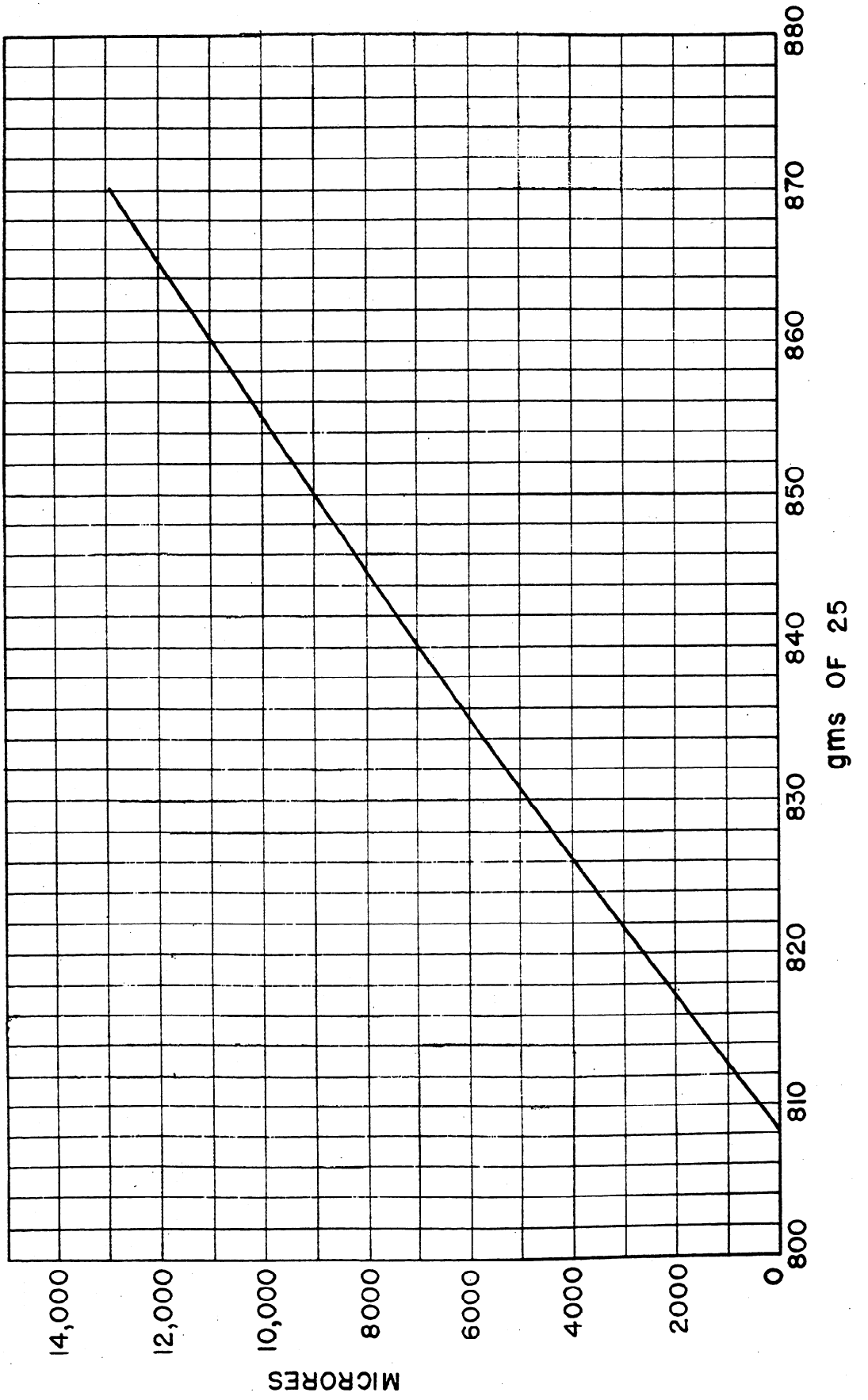


Figure 54

$$\sigma K = 1.219 \frac{M_{25}}{M_{25} + 177^{-1}}$$

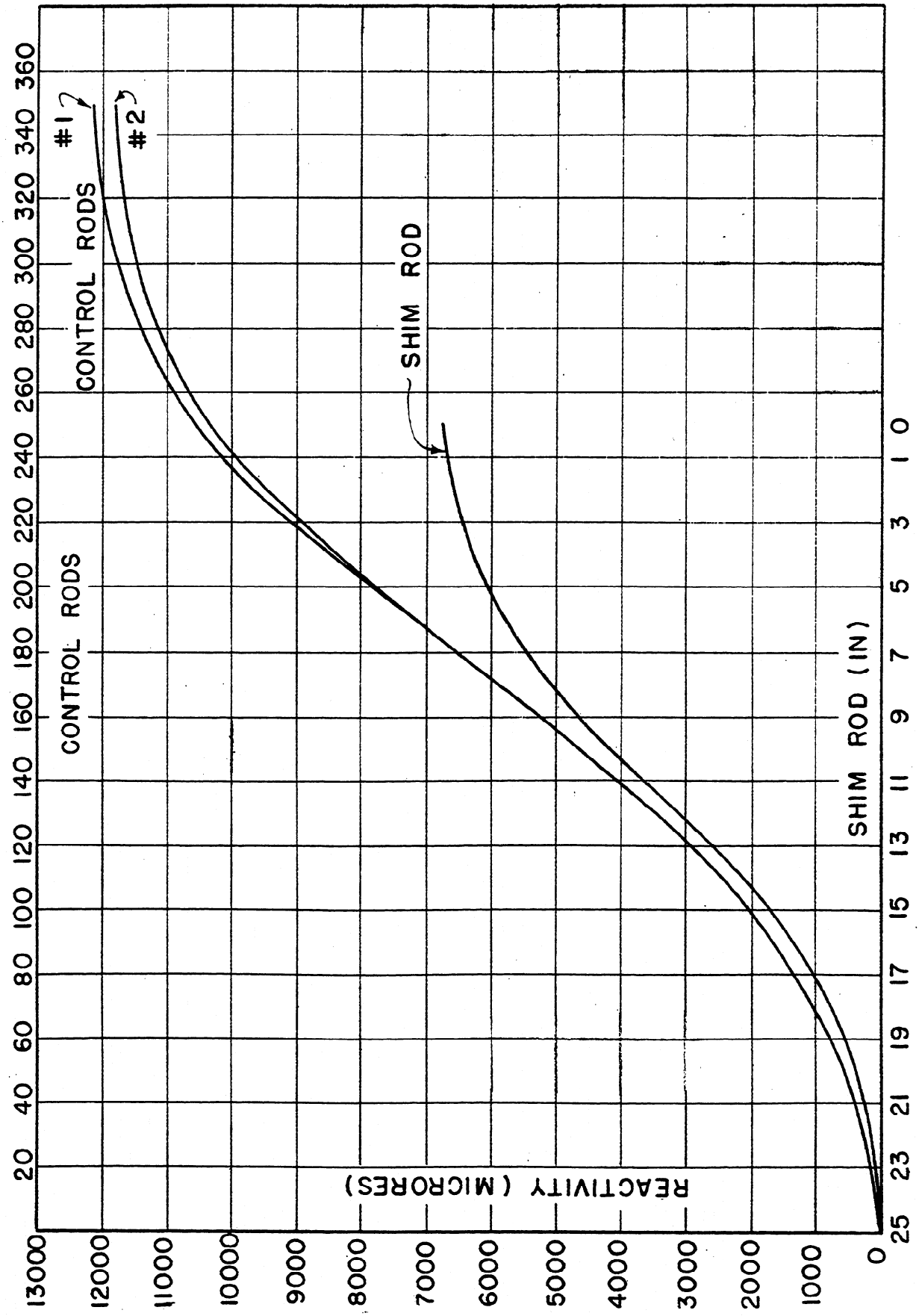

REACTIVITY (MICRORES)
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
CONTROL RODS
#1
#2
SHIM ROD
SHIM ROD (IN)
0
1
3
5
7
9
11
13
15
17
19
21
23
25

Figure 55

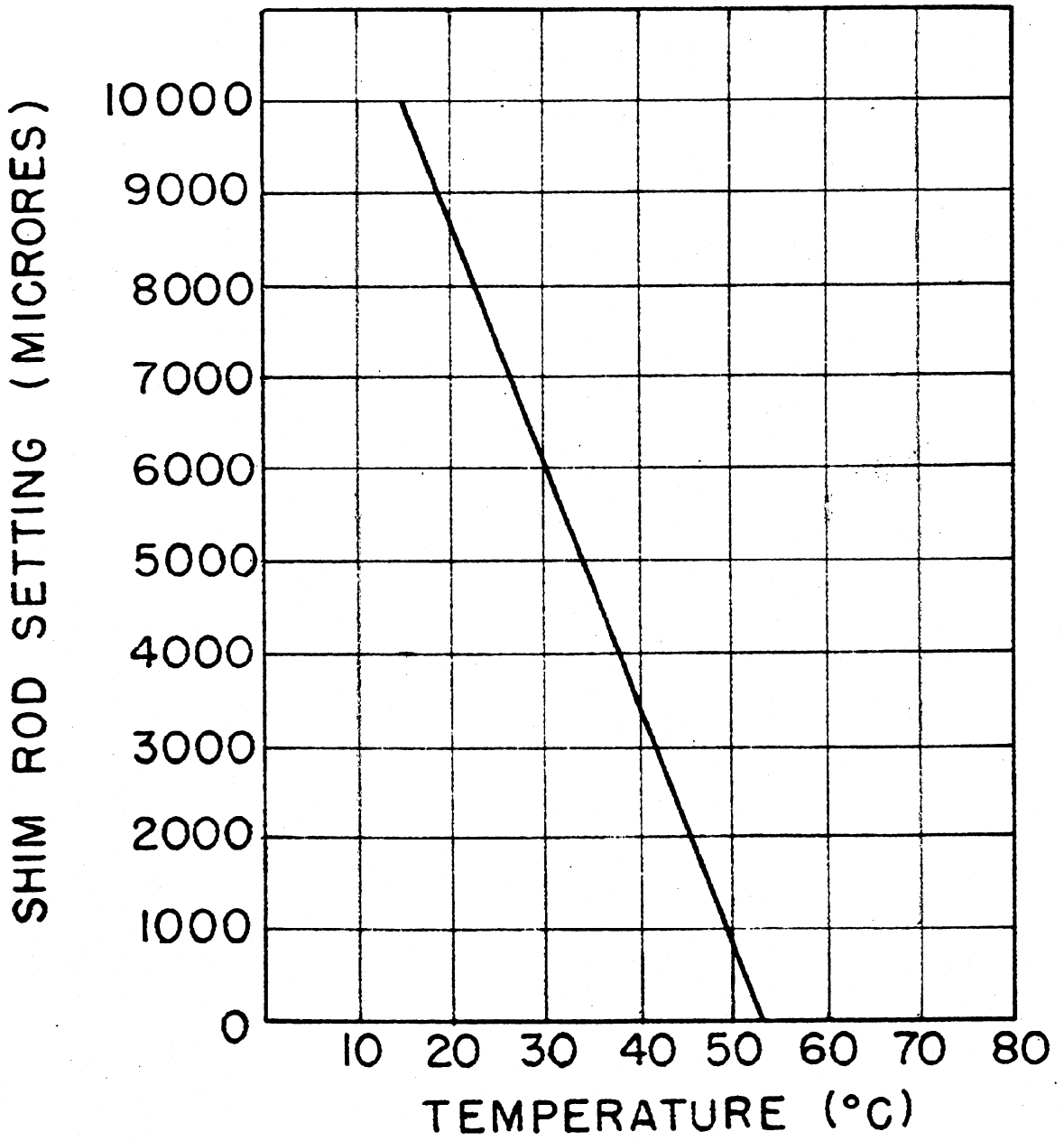


Figure 56

262 μR = 1° C = 1.33 gram 25 Equivalent

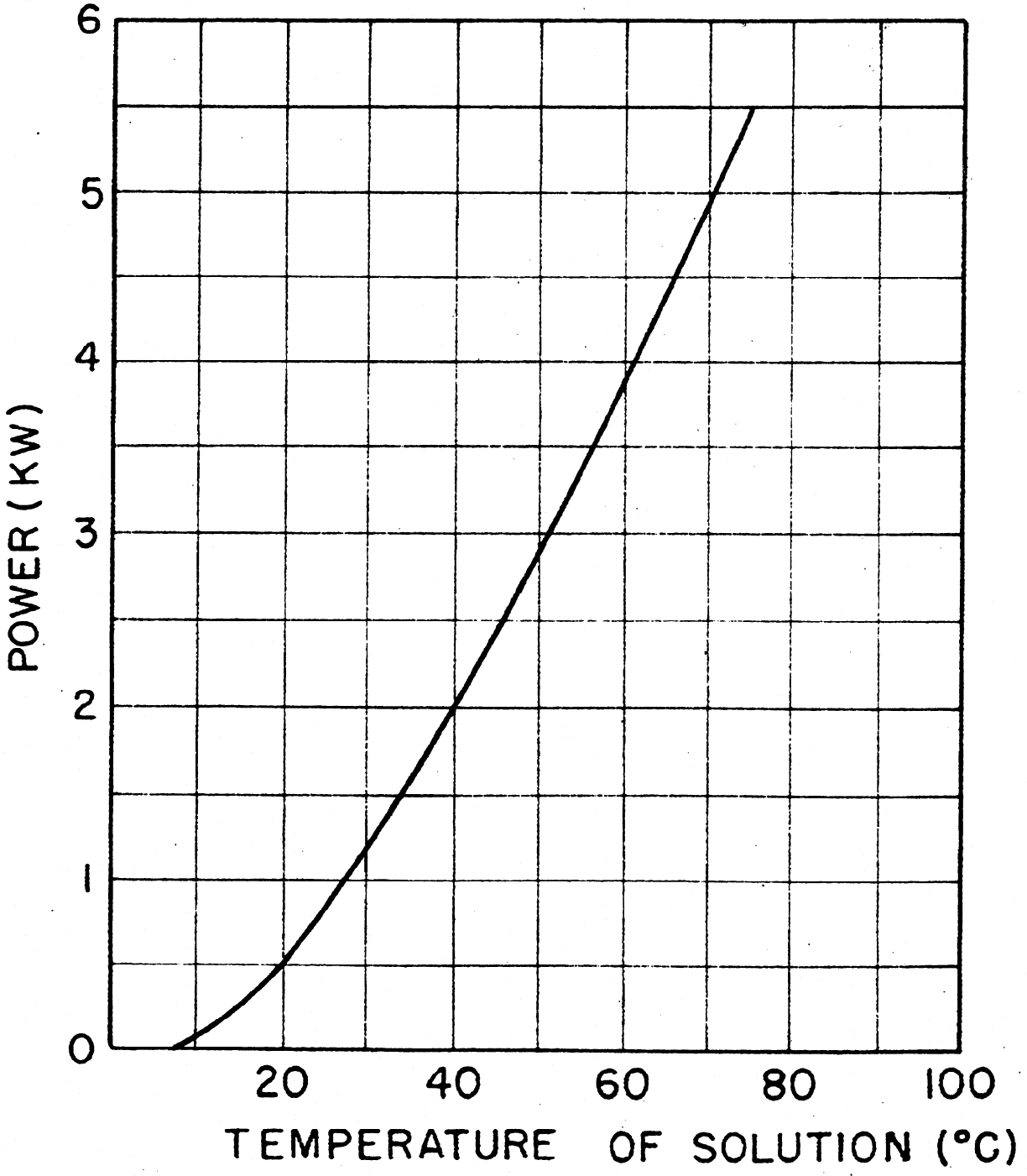


Figure 57

Equilibrium Running Conditions

for 50 cc/sec Inlet Water at 8°C

(4) Loss of nitrate and water

After the hypo had run for several hundred kilowatt hours it was observed that its reactivity had increased considerably. Chemical analysis of the solution indicated a 30 per cent deficit in the original nitrogen content. The uranyl nitrate was apparently gradually being converted into basic nitrate and the free nitrate carried off in the flushing air. Laboratory tests indicated that the solution would precipitate if the loss of nitrogen exceeded 35 per cent. The addition of nitric acid formed the normal nitrate again when added to the test solutions.

At this time it seemed advisable to add some acid but maintain the nitrogen concentration about 20 per cent lower than the original value since this permitted operation at higher power with the available material.

Previous additions to the solution had consisted of distilled water to make up for that lost by electrolysis.

The loss of nitrate necessitated additions of concentrated nitric as well as water in the ratio of about 2.8 water to acid. After 1000 kilowatt hours of operation as mentioned above a precipitate was formed. The laboratory tests of a precipitate forming only at 35 per cent deficit in nitrogen were apparently not born out when the material was under intense irradiation and imperfect mixing existed immediately after additions were made. The nitrogen concentration was then brought back to that for normal uranyl nitrate and no further precipitation has occurred to date (July 1946) with an additional 2500 kilowatt hours of operation.

Additions now are in the ratio of 1.4 water to acid to maintain

the normal concentration of nitrogen. About 6 cubic centimeters of water and acid are required per kilowatt hour of operation.

(5) Controls and operational procedure

The control panel is shown in Figure 58. The panel rack on the extreme right contains the following units from top to bottom: (1) counting rate meter with adjustable neutron level safety tripper; (2) power integrator scale of 256 (both (1) and (2) operate from a small U235 chamber); (3) row of trouble lights to indicate if running conditions are right, i. e., air flow, water flow, control rods out from zero position, cadmium curtain up, safety catcher bucket empty; (4) galvanometer shunts and cadmium curtain motor control; (5) Esterline-Angus recorders of neutron level, one on BF_3 safety monitor, the other on small U235 chamber

The second rack contains (1) bubbler level indicator; (2) main power lock safety tripping circuit, BF_3 chamber intensity meters and safety rod raising switch; (3) galvanometer scales; (4) control rod selsyns, ratchet switches and reset mechanism; (5) potentiometer for supplying galvanometer bucking voltage.

The third rack has (1) water-and air-flow meters with control valves; (2) light-indicating low-water flow with coolers off; (3) level indicator selsyn control with level scale; (4) shim rod position scale and raise-lower variac control; (5) sphere temperature and power meters.

The fourth rack contains (1) clock; (2) scale of 256 for monitoring thermal column with midget U235 chamber; (3) automatic power level selector; (4) inter-communication system.

The fifth rack contains (1) twelve-point thermocouple recorder for sphere, tamper, inlet and outlet water temperatures and counting rate meter (this unit not regularly used); (2) potentio-

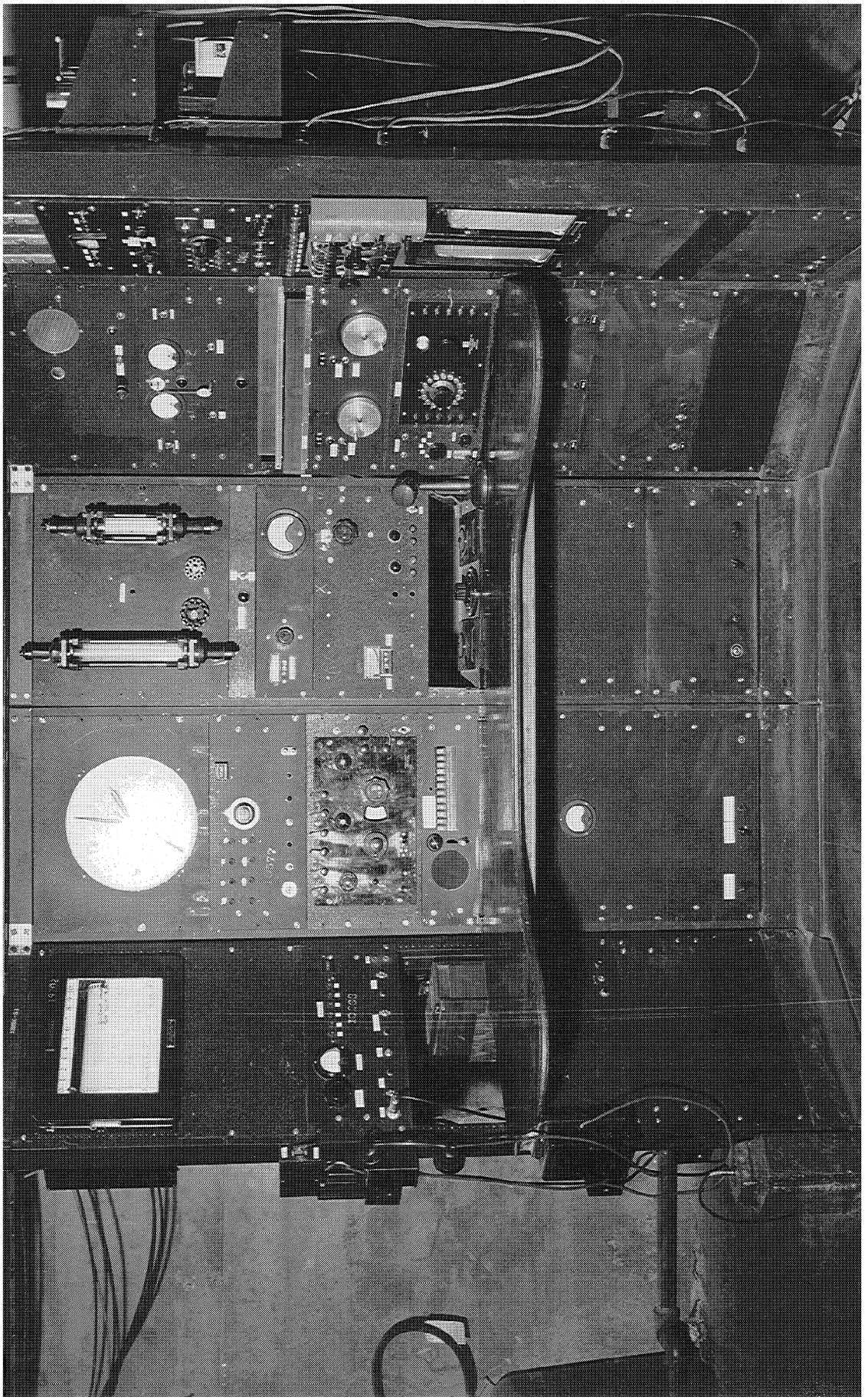


Figure 58

meter for temperature checking; (3) GM counter to detect fission gas or other radioactivity in the control room.

Typical operating procedure is as follows:The U235 chamber power integrator, solution level and sphere are recorded. Flushing air (50 cubic centimeters per second) and cooling water (.8 gallons per minute) are turned on. The direct-reading galvanometer is set on maximum sensitivity. The desired deflection and bucking voltage for the high sensitivity or null galvanometer are read from the available curve for the particular power at which it is desired to run. The control and two shim rods are checked for "in position". The safety rod is raised. The control rods are then slowly raised one at a time and the galvanometer deflection observed. The position of the control rods for the boiler to start will depend on the initial temperature of the sphere. Because of the variations in the background activity of the solution, the rate of rise of the neutron flux depends on the past running history of the boiler. Considerable caution is therefore necessary when first starting, this is especially true until the multiplication rate is actually known from the galvanometer or counter. In order to eliminate this "blind" region in starting, plans are underway to connect a chamber, as shown in Figure 47, to the direct reading galvanometer. The chamber will be lowered sufficiently to give a slight galvanometer reading for the source neutrons. When the desired reading is obtained on the direct reading galvanometer, the bucking voltage is connected to the null galvanometer which at full sensitivity represents 50,000 centimeters per kilowatt. If the automatic control is used, the bias voltage is adjusted for the desired power operation, and it will run one of the control rods to maintain constant power. In this

running condition the row of 10 trouble lights is on. If any one of these goes out, one can tell at a glance whether water, air temperature, etc., is abnormal.

The boiler responds very rapidly to control rod positions and these can be changed at almost whatever speed the operator desires to turn the knob. This means that an experienced operator can bring the boiler up to full power or go from a low to a high level in a few seconds. This rapid response is accomplished by letting the boiler rise with the rod out "too" far so that one is running a considerable amount supercritical. As the desired power is approached the rod can be run back rapidly. A visual observation of the neutron intensity on one of the recording meters enables one to have an almost vertical rise with an immediate leveling off at the desired intensity level.

4.3-4 Performance

(1) Flux and power

With an inlet water temperature of about 8 degrees C obtained by precooling and the 870 grams of U^{235} in the boiler it is possible to run continuously 5.5 kilowatts without exceeding a solution temperature of 80 degrees C. There is still some excess reactivity left to permit experiments with absorbing materials near the sphere when running at this power.

The increase in power above that originally planned was possible because of the overdesign in the cooling system and the absence of violent frothing or bubbling in the solution.

The power measurements were based on inlet and outlet water temperatures. Measurements made with standardized manganese foils and a small fission chamber gave the following flux intensities in the thermal column. Cadmium ratios were obtained

with standard indium foils.

Position in inches	Cd ratio	$n\upsilon$/KW
0	---	$.83 \times 10^9$
2	500	6.9×10^8
12	2,500	1.5×10^8
24	50,000	$.26 \times 10^8$
36	90,000	

All distances are measured from the cadmium curtain which is four feet from the outer end of the column.

The equation for the flux in the column from the above data is

$$n\upsilon/KW = .83 \times 10^9 \, e^{Z/29.4}$$

where Z is the distance from the cadmium curtain and the relaxation length is 29.4 centimeters.

For numerous experiments where a strong thermal neutron beam was desired a cavity was made in the thermal column 24 3/4 inches x 24 3/4 inches x 24 inches one foot from the outer end. This gave a flux of 7×10^5 per kilowatt on a target one foot in front of the thermal column; the cadmium ratio using the cavity is about 1500.

Experiments with fast neutron beams can be done by removing the tamper stringer which surrounds the 1 inch transverse hole to the boiler. This exposes the end of the "glory hole" and 3 inch x 3 inch area of the sphere itself. The following flux measurements were made just beyond the concrete shield with various detectors to get some idea of the neutron energy distribution.

Detector	Flux per kilowatt
U^{235} chamber	5×10^5
U^{238} chamber	4×10^6
N_p^{237}	5×10^6
Cd ratio with Indium foils	4.5

Measurements made 8 feet from the concrete showed a well collimated beam the same width as the aperture in the concrete.

Gamma ray measurements made with the 3 inch x 3 inch area of the sphere exposed gave an intensity of about 3,000 curies out of the 4¼ inch x 4¼ inch opening in the concrete shield. These measurements were made a short time after the boiler was shut off after a run of several hours at high power.

Distribution measurements were taken through the tamper and "glory hole" with manganese and gold wires. The following fluxes relative to that at the center of the sphere were obtained.

	Au	Mn
Center sphere	1	1
Edge sphere	.8	.8
Max in BeO	.85	.84
Edge of BeO	.66	.68
Outer edge graphite	.045	.036

The flux at the center of the sphere in the glory hole is about 5×10^{10} per kilowatt using small calibrated Mn foils.

(2) Steadiness of operation

The water boiler is inherently not as steady in operation as the large graphite piles. This is probably due to the large convection currents and bubble formation taking place especially when operating at high power. If the boiler runs itself after reaching temperature equilibrium, it will maintain a constancy of about .2 per cent when operating at 1 kilowatt. The intensity level can, however, be maintained to .01 per cent or better when operating at 1 kilowatt or over when the full sensitivity of the bucking galvanometer is used. This requires almost continuous motion of the control rods; the automatic control gives about the same accuracy as the best hand control.

Measurements have been made to determine the shutting off factor for the boiler after various running conditions. If three rods are dropped simultaneously the neutron intensity drops a factor of 6 within the first second and then there is a gradual decrease due to the delayed neutrons and gammas from the fragment decay reacting with the beryllium in the tamper. Only a very small difference in the background activity was observed however between runs where the boiler had been operating for 50 kilowatt hours immediately before and one where the boiler had not been in operation for 48 hours. This indicates that at least rough critical measurements could be made in spite of the beryllium in the tamper.

4.3-5 Modification and Conclusions

The water boiler has run approximately 3500 kilowatt hours at this time (July 1946). During this period it has become evident that no major modifications are necessary from the point of view of satisfactory operation.

Corrosion after the initial pickling in a uranyl nitrate solution has not been detectable in a spectroscopic analysis for Cr, Fe and Ni. The production of fission fragment contamination is also not detectable. A comparison of column 2 and 3 of Table 4.3-5 indicates negative corrosion.

The only features which have given trouble were (1) handling of the exhaust gases, (2) precipitation of the solution when run with too low a nitrogen concentration.

The exhaust gases are highly radioactive and corrosive. They carry away varying fractions of gaseous fission fragments depending on their half life. An analysis of the gases (3) indicates that those with half lives of less than 1.5 seconds are not removed due to the slow rate of sweep in the solution itself. Kr^{89} for example, with a half life of 2.6 minutes was swept out to the extent of 30 per cent. Some of the longer lived gases are removed about 100 per cent. These experiments seem to indicate that roughly 30 per cent of the total fission fragment activity is carried out by the flushing air.

Nitric acid fumes and the high moisture content in the solution require the use of stainless steel for the entire length of the exhaust pipe unless there exists a suitable moisture trap. Difficulties have been encountered from using silver solder and copper tubing for parts of the exhaust line even though removed some 25 feet from the boiler with a safety bucket between to catch any solution.

Due to the high radioactivity of the gases it may be somewhat difficult to dispose of them. In isolated sections of the country such as Los Alamos these can be released into the atmosphere if the distance is sufficient so as to cause no G. M. counter disturbance at the laboratory; this may require 3,000 - 5,000 feet of line or a high stack if the air currents are suitable. In congested communities the gas disposal problem becomes more serious. Possible other solutions might be the following.

(1) The hydrogen and oxygen recombined. Tests are underway whether

TABLE 4.3-5

Corrosion Record

	Soup Nov. 3, 1944 Before Precipitate	Aug. 8, 1945 after put back in boiler	May 27, 1946 Now
Be	ND < .05	ND > 0.1	ND < .05
B	.2	1.	1
Na	20	100	ND < 5
Mg	20	35	> 5
Al	< 10	20	ND < 5
Si	1.5	100	200
P	ND < 20	50	ND < 2
Ca	50	500	200
Cr	< 10	15	15
Mn	2	7	30
Fe	(Nov.29) 50 (Dec. 26) 125	500	500
Ni	5	15	ND < 1
Cu	2	200	100
Zn	20	150	50
Pd		ND < 1	ND < 1
Ag	.3	.2	5
Cd	.09	30	15
Sn	5	20	30
Sb		ND < 2	ND < 1
Pb	< 1	200	50

The large change in composition of the solution between columns 1 and 2 is due to impurities picked up in the handling of the solution after the formation of the precipitates described in the

the nitrogen loss is due to evaporation or is in a form which can be recombined. This method, if feasible, would retain all the fission activity in the boiler and remove the need for flushing air. The boiler could be virtually be sealed up if sufficient space for expansion is left.

(2) Large underground tanks to store the gas. This is probably not a good method due to the large total volume of gas used for flushing.

(3) Freezing out most of the activity in a series of traps. During period when not in operation the active gases and fission fragments trapped could be released and stored in comparatively small containers. This method avoids the necessity of storing the large amount of flushing gas normally used (3,000 cubic centimeters per minute).

The precipitation problem encountered after 1,000 kilowatt hours of operation seems definitely to be due to operating at 20 per cent low in the original nitrate concentration. The precipitation which formed was soluble in nitric acid. Laboratory tests indicated that no precipitate should form until the nitrate was 30-35 per cent low, but this figure apparently is incorrect when the solution is under irradiation and water additions are made with only convection currents for mixing. For the last 2,000 kilowatt hours the nitrate has been held close to the original value (53.5 milligrams of N per ml); no evidence of any further precipitation has occurred. Since the cause for this trouble was not immediately evident, some modifications (see 3.2-2(g)) were made.

Due to the low corrosion and contamination rate of the boiler solution a slight simplification in the original design may be advisable. It has been found that all additions and removals of solution can be done quite satisfactorily from the top with the aid of a small vacuum pump. The average

activity of the solution 48 hours after operation is about 10-20 microseconds per cubic centimeter. This permits removal of the "hot" solution from the top in small batches without the need of elaborate shielding. Since all operations have been done in this way, the need of a lower pipe and dump valve becomes unnecessary; the lower hemisphere could then be spun without an outlet hole.

Further modifications might be useful since active material is now made in large quantities. The tamper could be made entirely of graphite. This would require approximately 35 per cent more material. The use of graphite would simplify the fabrication of the inner tamper and make the boiler more useful for critical measurements. Whether a cylindrical construction would be more advantageous than the sphere seems somewhat doubtful. In the first place the cylinder would require somewhat more material and though possibly somewhat easier to fabricate, it would require more welded seams. On the other hand the tamper fitting would be simpler; this latter point would probably only be of importance if a beryllium tamper rather than graphite is used.

The cost of constructing a water boiler assuming the government furnishes the enriched material should be considerably less than for a medium size cyclotron. The total electronic equipment necessary is considerably less. The cost of cadmium, lead, reenforced concrete, and high purity graphite should not exceed $40,000. The upkeep appears to be extremely low.